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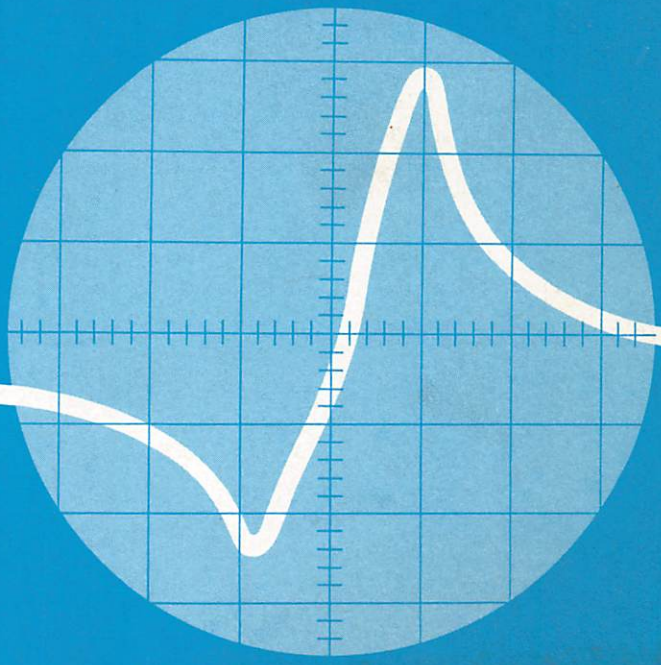

# PIEZOELECTRIC TECHNOLOGY

## DATA FOR DESIGNERS

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## GENERAL INFORMATION

### Piezoelectricity Defined

Piezoelectricity is "pressure electricity". It is a property of certain crystals such as quartz, Rochelle salt, tourmaline, barium titanate. As the name implies, electricity is developed when pressure is applied to one of these crystals. The reverse effect also is present. When an electric field is applied the crystal changes shape. Piezoelectricity was discovered by Pierre and Jacques Curie in the 1880's.

### Piezoelectric Materials

In this booklet we will present data for piezoelectric materials in common use as—electromechancial transducers. These include Rochelle salt, ammonium dihydrogen phosphate (ADP) and lithium sulphate crystals, barium titanate and four variations of lead zirconate—lead titanate (PZT) ceramics. The ceramics are polycrystalline in nature and do not have piezoelectric properties in their original state. Piezoelectric behavior is induced in these materials by a polarizing treatment (poling).

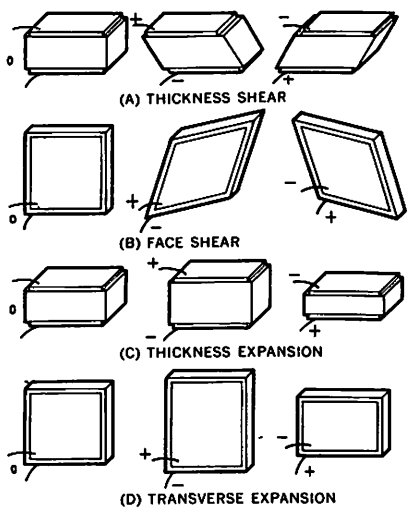



Fig. 1. Basic Deformations of Piezoelectric Plates.

### Piezoelectric Actions

The deformation of a body of piezoelectric material that results from the application of an electric field and conversely the nature of the deforming forces required to develop an electric charge depend on the type of piezoelectric material. The possible piezoelectric actions are illustrated in connection with plates of piezoelectric material in Fig. 1. Generally two or more of these actions are present simultaneously. In some cases one type of expansion is accompanied by another type of contraction which compensate each other resulting in no change of volume. For example, the expansion of length of a plate may be compensated by an equal contraction of width or thickness. In some materials, however, the compensating effects are not of equal magnitude and net volume change does occur. In all cases, the deformations are very small when amplification by mechanical resonance is not involved. The maximum displacements are on the order of a few microinches.

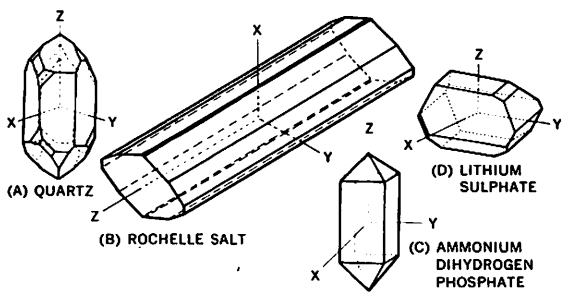



Fig. 2. Crystals and Axes.

### Piezoelectric Plate Designations and Crystal Cuts

The magnitude and character of the piezoelectric effect in any piezoelectric material is greatly dependent on the orientation of the applied force or the electric field with respect to the axes of the material. These axes constitute a coordinate system which was established by crystallographers for the purpose of simplifying discussions of crystals. In the case of piezoelectric ceramics, the axes are established with reference to the direction of the electric field originally applied during the poling operation. To illustrate typical forms of whole crystals and to show the crystallographic axes with respect to these crystals, a number of crystals are shown in diagrammatic form in Fig. 2.

Piezoelectric crystal elements are made from slabs cut from the crystal rather than from the whole crystal itself. These slabs are known as "cuts" and are identified by the axis perpendicular to the largest face of the cut. Thus, if a slab is cut with its major faces perpendicular to the X crystallographic axis, it is known as an "X-cut". The plates cut from these slabs are further designated by their angular orientation with respect to the other two crystal-

lographic axes. A plate cut from an X-cut slab, with its edges parallel to the Y and Z axes, is designated as a "0° X-cut plate"; whereas, if the edges are at a 45° angle with respect to the Y and Z axes, it is designated as a "45° X-cut plate", etc. (The Standards on Piezoelectric Crystals, 1949, of The Institute of Radio Engineers, designate plate orientation in a different manner. For example, a 45° X-cut Rochelle salt plate is designated as xyt 45°. Since many people are familiar with the method of designating plates which we have described, and since this method is still in most common usage, we will use it throughout this booklet.)

**Piezoelectric Actions Available from Various Materials**

In piezoelectric ceramic materials, the directions of the electrical and mechanical axes depend upon the direction of the original d.c. polarizing field. During the poling process a ceramic element experiences a permanent increase in dimension between poling electrodes and permanent decrease in dimensions parallel to the electrodes.

When a d.c. voltage of the same polarity as the poling voltage but smaller magnitude subsequently is applied between the poling electrodes, the element experiences further but temporary expansion in the poling direction and contraction parallel to the electrodes. Conversely, when d.c. of opposite polarity is applied, the element contracts in the poling direction and expands parallel to the electrodes. In either case, the element returns to the original poled dimensions when the voltage is removed from the electrodes. These effects are shown, greatly exaggerated, in Fig. 3. The thickness and transverse effects are not of equal magnitude, accordingly there is a small volume change when voltage is applied to the electrodes.

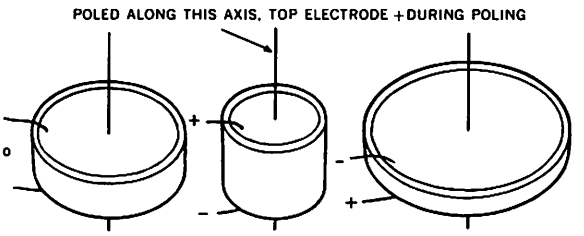



Fig. 3. Basic Deformations of Piezoelectric Ceramic Plates.

When compressive force is applied in the poling direction or tensile force is applied parallel to the electrodes, the voltage that results between electrodes has the same polarity as the original poling voltage. Reversing the direction of the applied force reverses the polarity of the resulting voltage between electrodes.

When the poling electrodes are removed from a ceramic element and the element is provided with signal electrodes perpendicular to the poling direction and a voltage is applied, shear takes place around an axis perpendicular to both the poling and signal directions. This is illustrated in Fig. 4. When shear forces are applied, corresponding voltage appears between the signal electrodes.

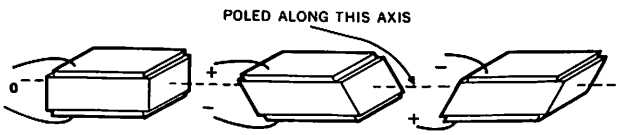



Fig. 4. Shear Action of Ceramic Plates.

Rochelle salt and ADP provide face shear action (Fig. 1B). The X-cut of Rochelle salt has the strongest piezoelectric action of any material commercially available but only in a very limited temperature range. The piezoelectric activity of the Z-cut of ADP is sufficiently strong to make this crystal very useful in underwater sound applications. Plates of Rochelle salt and ADP cut with edges at 45° to the other two axes (parallel to the diagonals of face shear plates in Fig. 1B) exhibit transverse expansions of opposite sense in the length and width directions as illustrated in Fig. 5.

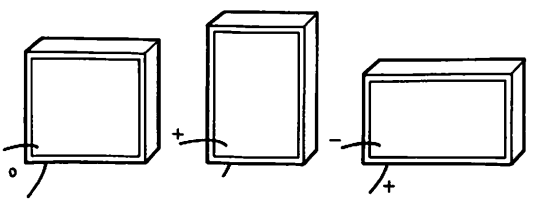



Fig. 5. Action of 45° X-Cut Rochelle Salt and 45° Z-Cut ADP.

The Y-cut of lithium sulphate is the only cut for this material in common use. It has a strong thickness expansion effect and, in addition, has two much weaker transverse expansion effects (length and width) which are opposite in sign, but unequal in magnitude. These transverse effects are much weaker than the thickness effect, and thus compensate only to a slight degree resulting in a substantial volume expansion.

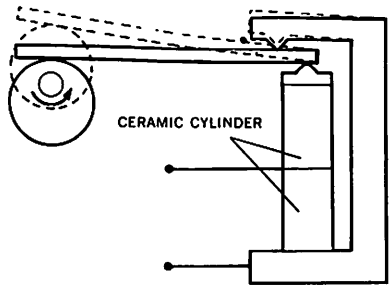



Fig. 6. High Voltage Generator.

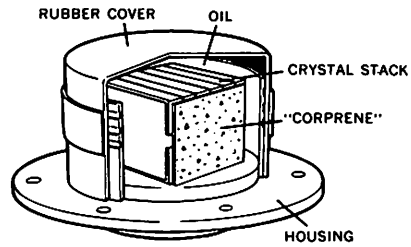



Fig. 7. Underwater Sound Transducer.

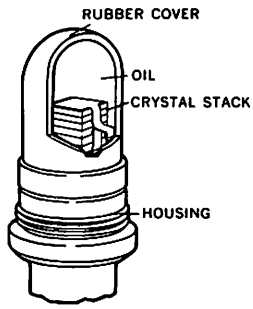



Fig. 8. Measurement Hydrophone.

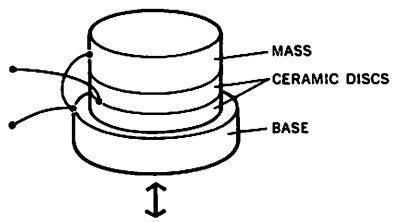



Fig. 9. Compression Accelerometer.

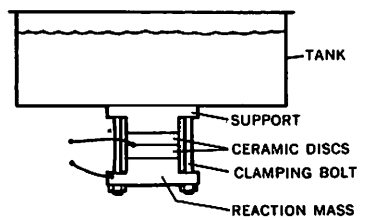



Fig. 10. Ultrasonic Cleaning Transducer.

## Applications of Simple Piezoelectric Elements

Fig. 6 illustrates the use of simple piezoelectric elements in a high voltage source for gasoline engine ignition. A cam driven by the engine actuates a lever which applies varying axial force to two PZT-4 ceramic cylinders. The cylinders are electroded on their end faces and are stacked with like polarity electrodes facing each other so that the driven and support ends may be at ground potential. A device of this type has been used successfully on small lawn mower gas engines developing ignition potentials in the order of 20,000 volts.

The underwater sound transducer shown in Fig. 7 illustrates an application of ADP crystal plates. A group of transverse expander (45° Z-cut) plates is stacked together with interleaved, parallel connected foil electrodes. The ends of the plates of the crystal stack act together in a piston-like action and are coupled to the water through the rubber housing and the oil which surrounds the stack. Since the edges of the plates are also pressure sensitive, acoustic shielding of a material such as "Corprene" or "Cell-tight" foam rubber is placed around these edges to prevent their piezoelectric action from coupling to the oil and cancelling the acoustic output of the exposed ends.

Fig. 8 illustrates a sound pressure measurement hydrophone which employs, in this instance, a stack of thin parallel-connected Y-cut lithium sulphate plates. Since this material has a strong piezoelectric volume expansion effect, it is not necessary to provide acoustic shielding for the edges of the plates.

Fig. 9 illustrates a simple form of piezoelectric accelerometer suitable for measuring vibratory accelerations occurring over a wide range of frequencies. It consists of two PZT-5 ceramic discs sandwiched between a mass and a supporting base. The assembly may be glued or clamped together. Vibratory acceleration applied to the base in the direction indicated produces corresponding forces of compression across the thickness of the discs due to the inertia reaction of the mass. Thus voltages corresponding to the applied acceleration are generated in the discs.

Fig. 10 illustrates the use of piezoelectric ceramic elements in an ultrasonic cleaning application. Two PZT-4 ceramic discs are clamped between a light metal support and a reaction mass. The support is securely attached to the cleaning tank. The composite assembly has a mechanical resonance determined by the combined effects of mass and stiffness in the metal and ceramic parts. When the ceramic discs are driven by ac power at the frequency of mechanical resonance, the assembly vibrates at high intensity inducing violent agitation of the liquid in the tank.

## Application of Shaped Ceramics

Since piezoelectric ceramic materials can be fabricated in a wide range of sizes and shapes, they lend themselves to designs for particular applications which would be difficult, if not impossible, to achieve with single crystals. Fig. 11 illustrates a typical underwater transducer which utilizes a hollow ceramic cylinder polarized through the wall thickness. It is approximately the equivalent of a length expander plate bent into a cylinder. In this application the ends of the cylinder are capped to shield the inner cylindrical surface from the acoustic medium. Since the outer cylindrical surface exposed to the water is of large area in comparison to the cross-section of the ceramic material, the mechanical impedance of the element is much lower than a solid element of the same dimensions, which permits a better acoustic match between the piezoelectric element

and the medium through which it is to operate.

Fig. 12 illustrates use of thickness shear adapted to a cylindrical shape. Before assembly, the ceramic cylinder was polarized in the length direction employing temporary end electrodes. Then permanent cylindrical electrodes were applied and the element cemented to the central supporting stud and the cylindrical weight added. Vibratory acceleration applied to the base in the direction indicated produces corresponding shear stresses in the walls of the cylinder due to the innertia reaction of the mass. Thus voltages corresponding to the applied acceleration are generated in the cylinder.

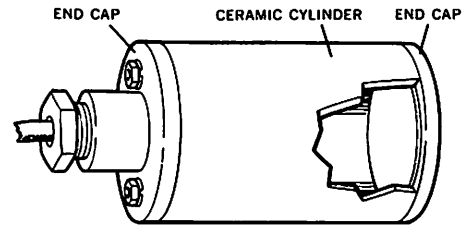


Fig. 11. Underwater Sound Transducer.

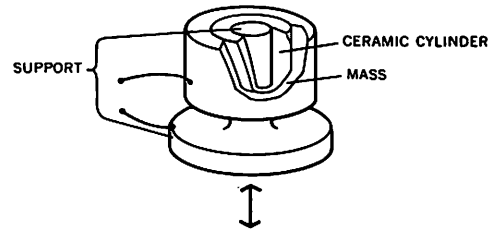


Fig. 12. Shear Accelerometer

### Mechanical and Acoustical Impedance Considerations

The mechanical or acoustical impedance of crystal plates or ceramic shapes is of the same order of magnitude as that of solids or liquids. For this reason, these elements are well suited to underwater sound applications and those mechanical applications where large forces with small displacements are involved. Since these impedances are of several orders of magnitude greater than those of gases, the transfer of energy to air, for example, is poor. For air acoustical applications and such mechanical applications as phonograph pickups, where small forces with comparatively large displacements are involved, some system of levers is indicated to obtain a better impedance match.

### "Bimorphs" and "Multimorphs"

"Bimorph" is the trade name for a flexing-type piezoelectric element developed by Clevite, which has the capacity for handling larger motions and smaller forces than single piezoelectric plates. This element consists of two face-shear plates or two transverse-expander plates secured together face to face in such a manner that a voltage applied to the electrodes causes the plates to deform in opposite directions, resulting in either a twisting or a bending action. Conversely, depending on its construction, mechanical twisting or bending of the element will cause it to develop a corresponding voltage between electrode terminals.

"Multimorph" is the trade name for a single piece ceramic bender element that operates on the same principle as the "Bimorph". It is illustrated in Fig. 13. The graphite coatings on the walls of the tubular openings running the length of the element together correspond to the inner electrode of the "Bimorph".

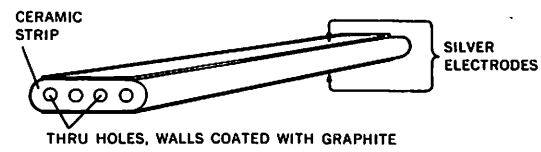


Fig. 13. "Multimorph"

The displacement of the "Bimorph" or "Multimorph" in response to an applied voltage is many times greater than the corresponding displacement of a single plate. Thus "Bimorphs" and "Multimorphs" have, in effect, "built-in" levers to provide or require much greater motion but less force than single plates.

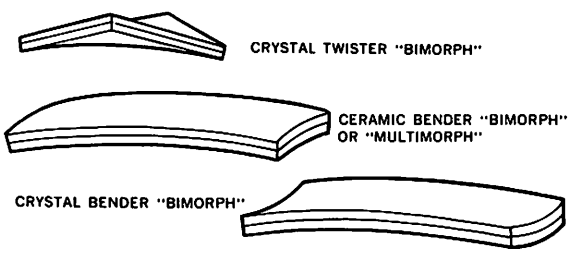


Fig. 14. Curvatures of "Bimorphs" and "Multimorph"

We have illustrated in Fig. 14, greatly exaggerated, the curvature developed in a twister and a bender crystal "Bimorph", and in a bender ceramic "Bimorph" or "Multimorph" with an applied voltage or, conversely, the twisting or bending which should be mechanically induced to cause the element to generate a voltage. Note the difference between the deformations of crystal and ceramic bender elements which arise from the differences in transverse expansion in the two materials.

The electrical connections to the "Bimorphs" may be arranged in different ways depending on the requirements of the application. The connections may be to the two outer electrodes, with no connection to the face to face electrodes in the middle of the assembly as shown in Fig. 15A. This is known as the series connection.

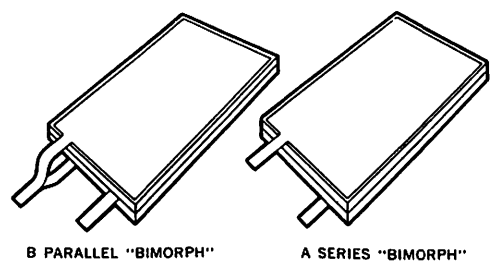


Fig. 15. Parallel and Series Connections

In the parallel connection, Fig. 15B, one lead goes to both outer electrodes, and the other lead goes to the face to face inner electrodes. The series and parallel connections cannot be used interchangeably for the same "Bimorph". In the case of crystal "Bimorphs", the required orientations of the two plates with respect to the crystal axes are different for series and parallel connections and accordingly the type of connection must be determined at the time of manufacture. In the case of ceramic "Bimorphs" and "Multimorphs", the type of connection depends on the direction of polarization in one plate with respect to the other, and accordingly also must be determined at the time of manufacture. The series connections develop twice the voltage of the parallel connections for the same driving force, but provide only half the displacement of parallel elements for the same applied voltage. The electrical impedance of the series element is four times the impedance of a parallel element.

**Mounting and Driving "Bimorphs" and "Multimorphs"**

The performance of a "Bimorph" is greatly influenced by the manner in which it is mounted and driven. An ideal mounting member should prevent any motion of the element at its mounting points in certain directions, while offering no resistance to the movement of these same points in other directions. An ideal driving member should impart the desired reciprocating or twisting motion without interfering in any way with the normal flexure of the element.

There are many ways of mounting and driving "Bimorph". Fig.16 illustrates several of the more common of these methods, with a three-corner mounting for a twister element shown at (A), a torsional mounting for a twister element shown at (B), an end supported center drive mounting for a bender element shown at (C), and a cantilever mounting for a bender element shown at (D). In the case of the three-corner mounted twister "Bimorph," illustrated in Fig. 16A, an ideal mounting should prevent the three corners from moving vertically with respect to the base, but these supports should not interfere in any way with the normal flexure of the element. A truly reciprocating drive connection in this same example would have to be supplied with some sort of pivot arrangement, since the angle of the drive pin with the crystal face is 90° only while the element is at rest.

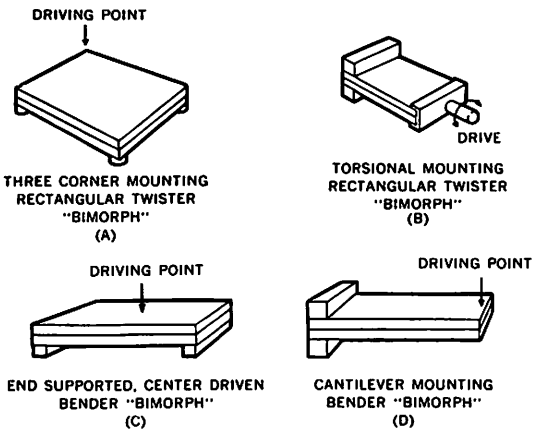



Fig. 16. Typical "Bimorph" Mountings

Ideal mounting and driving conditions can be approached in the laboratory but are generally far from realized in practical designs suitable for quantity manufacture. In practice, "Bimorphs" and "Multimorphs" generally are cemented to, or clamped between, soft rubber or plastic pads located at the appropriate mounting points. In some cases, the elements are cemented to rigid supports of small area, relying on flexibility of the cement, or the element itself, to permit normal flexure of the element as illustrated in Fig. 14. Of course, some of the energy which would otherwise be useful in the vibrating system is required to flex the mounting members thus reducing the sensitivity of the device. Nevertheless, practical considerations usually dictate the use of such mountings and they do offer the advantage over ideal mountings that they introduce some mechanical damping to the vibrating system, which is generally desirable for control of the frequency response of the device.

## Applications of "Bimorphs" and "Multimorphs"

Fig. 17 shows the use of Crystal Bender "Bimorph" elements (A) and Ceramic "Multimorph" elements (B) in stereo phonograph cartridges. The two elements of a cartridge are disposed at 90° to each other and at 45° to the record surface. One end of each element is supported in the cartridge housing by soft clamping pads. The "front" ends of the elements are embraced by a soft plastic member, the bottom of which engages a record stylus. Signals recorded in one wall of the record groove cause the stylus to vibrate and deform the plastic coupling member toward and away from the face of one element. The vibratory forces exerted on that element cause a corresponding signal voltage to appear at the terminals of the element. Since the other element is disposed at 90° to these vibrations, it receives no flexing forces and produces no signal voltage. In a like manner, signals recorded in the other wall of the record groove cause corresponding signal voltage to be developed only by that other element. Some mechanical vibratory energy imparted to the system by the record is dissipated in the soft coupling member and clamping pads thereby providing sufficient damping to control resonances in the system.

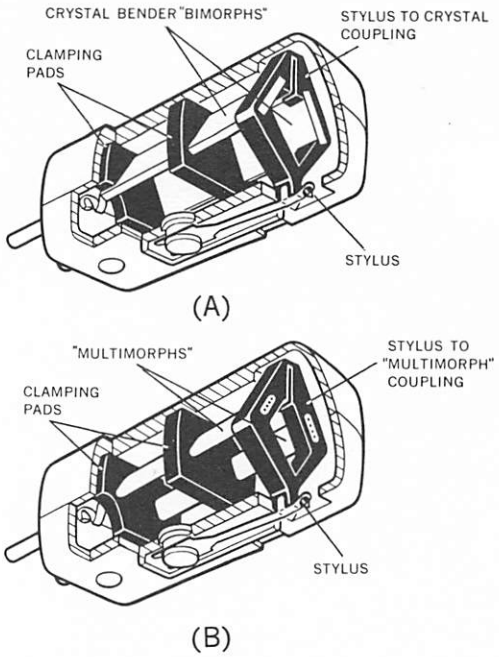



Fig. 17 Stereo Phonograph Cartridges
A. Crystal "Bimorph"
B. Ceramic "Multimorph"

A piezoelectric microphone employing a ceramic "Multimorph" is illustrated in Fig. 18. The "Multimorph" is supported near one end in a modified cantilever arrangement. The supports are metal angle pieces which serve also as electrical contacts to the two electrodes of the "Multimorph". The diaphragm is pressed against and cemented to the "free" end of the "Multimorph". Sound pressure variations acting on the diaphragm are imparted to the "Multimorph" as vibration forces tending to bend the "Multimorph". Thus the "Multimorph" generates voltages corresponding to the actuating sound pressure. Acoustic damping of the vibratory system is provided by a layer of cloth glued to the inner surface of the perforated cover.

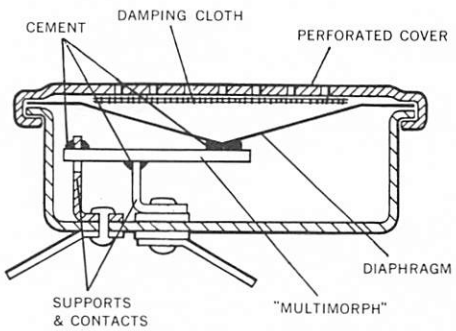



Fig. 18 "Multimorph" Microphone

Fig. 19 shows the construction of an earphone employing a parallel connected ceramic "Bimorph". The "Bimorph" is supported near its ends by metal clamps which also serve as electrical connections to the outer electrodes. A thin metal vane sandwiched between the ceramic plates of the "Bimorph" protrudes at one end for electrical connection to the inner electrodes. The diaphragm is coupled to the center of the "Bimorph" by a small plastic clip. Signal voltages applied to the "Bimorph" cause it to have corresponding vibrations which are imparted to the diaphragm. The diaphragm converts these vibrations to sound pressure variations at the users ear. A disc of porous metal in the cover introduces acoustic damping to control mechanical and acoustical resonances of the vibrating system.

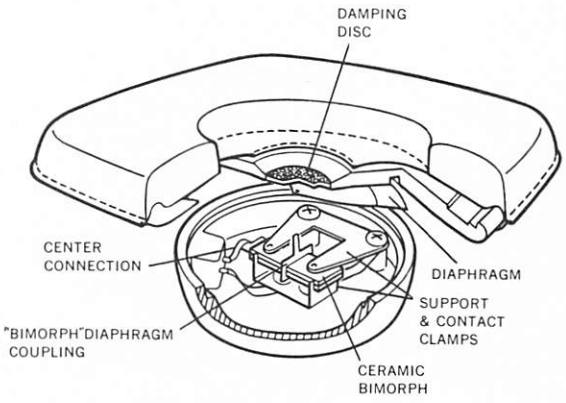



Fig. 19 Ceramic "Bimorph" Headphone

## Circuit Considerations

To obtain optimum performance from a piezoelectric device, the circuit to which it is connected must have certain characteristics which are dictated by the design of the device. In discussing this subject, it is convenient to divide piezoelectric devices into two broad categories—non resonant devices and resonant devices.

Non resonant devices are so named because they are designed to operate well below resonance, or over a relatively large frequency range, usually several octaves. Usually all or most of the operating frequency range lies below the resonant frequency of the device. However, in some cases, the useful frequency range includes the frequencies of one or more resonances. In such cases, heavy damping generally is employed. Non resonant devices include

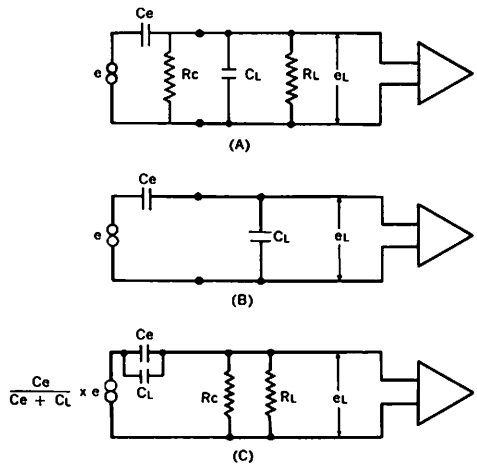



Fig. 20. Non Resonant Mechanically Driven Device

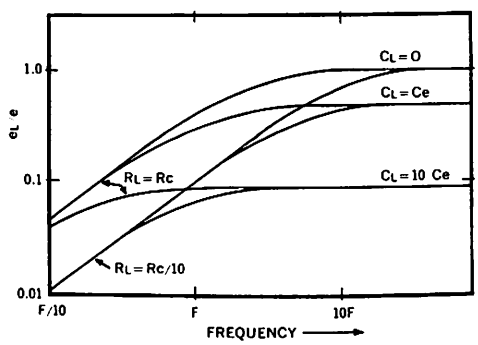



Fig. 21. Frequency Response of Non Resonant Mechanically Driven Device and Input Circuit.

phonograph pickups (Fig. 17), microphones (Fig. 18), headphones (Fig. 19), accelerometers (Figs. 9 and 12), high voltage sources (Fig. 6), and some underwater receiving transducers (Figs. 8 and 11).

Resonant devices are designed to operate at a single frequency, the mechanical resonance frequency of the device, or over a band of frequencies usually less than an octave, which band includes the resonance frequency of the device. Resonant devices include ultrasonic transducers (Fig. 10) and underwater power transducers.

### Circuit Considerations—Non Resonant Mechanically Driven Devices

For most practical circuit design purposes, a non-resonant piezoelectric generator device, such as a microphone or a phonograph pickup or accelerometer, together with the load on the device, may be represented by the equivalent circuit of Fig. 20A, where $C_e$ represents the capacitance of the piezoelectric element, $R_c$ is the shunt leakage resistance of the device, $C_L$ is the shunt load capacitance, and $R_L$ represents the load resistance. The values of the shunt leakage resistance and the capacitance of the piezoelectric element are dependent on the dimensions of the element and, in the case of leakage resistance, also upon the dryness of the surface. Under normal operating conditions, the value of this resistance is many times greater than the normal load resistance, ranging from several hundred megohms to many thousands of megohms. Generally, except at very low frequencies, the capacitances in the circuit have reactances very much lower than the circuit resistances. Under these conditions, the circuit reduces to the simple capacitive voltage divider circuit of Fig. 20B.

It can be seen from this circuit that the shunt load capacitance ($C_L$) of wiring, cable, and amplifier input does not bring about a relative loss of high frequency response as in the case of resistive or inductive sources shunted by capacitive loads, but instead reduces the output at all frequencies (except very low frequencies as discussed in the next paragraph).

By the application of elementary network theory, the basic circuit of Fig. 20A can be reduced to the equivalent circuit of Fig. 20C which is useful for analyzing the low frequency response. From this it can be seen that when the combined reactance of the piezoelectric and circuit capacitances in parallel approaches the combined resistance, the low frequency response begins to fall off. This analogous to the situation existing in conventional RC-coupled amplifiers.

The influence of the various circuit elements on frequency response is shown in a group of response curves illustrated in Fig. 21. It should be noted that the low frequency response can be extended, without increasing the shunt resistance, but at the expense of general output level, by adding shunt capacitance. This is a common expedient in connection with very low frequency operation of piezoelectric devices.

### Circuit Considerations—Non Resonant Electrically Driven Devices

In the case of non-resonant piezoelectric devices such as headphones which are electrically driven, the electrical impedance of the device may, for most practical purposes, be considered to be purely capacitive. For all frequencies well below the first mechanical resonance of the device, the electromechanical relationships are such that the displacement of the piezoelectric element from its normal position, at any instant, is directly proportional to the electric charge applied at that instant. From the relationship that voltage = charge/capacitance, it can be seen that the instantaneous displacement is

also directly proportional to the instantaneous applied voltage. Fig. 22 illustrates diagrammatically various basic circuit relationships and the various response characteristics of piezoelectric devices operating under these conditions.

It can be seen in Fig. 22A that "constant amplitude" operation occurs when the piezoelectric device is driven by a low impedance or "constant voltage" source. Fig. 22B shows that "constant velocity" operation occurs when the device is driven by a high resistance or "constant current" source. Fig. 22C shows that "constant amplitude" operation also occurs when a piezoelectric device is driven by a "constant charge" source, which may take the form, for example, of a low impedance source in series with a small condenser.

### Circuit Considerations—Resonant Devices

The electrical impedance of a piezoelectric device is in reality more complicated than the simple capacitor representation generally employed in discussing non resonant devices. A more proper representation would be a capacitor representing the static capacitance of the piezoelectric element, shunted by an impedance representing the mechanical vibrating system. In most non resonant devices, the latter impedance may be approximated by a capacitor. Therefore, we have a capacitor in parallel with a capacitor—hence the single capacitor representation.

In devices designed for operation at resonance, the impedance representing the mechanical system may become, at resonance, a resistance of relatively low value and this is shunted by the same static capacitance.

The shunt static capacitance generally is undesirable, whether the device is designed for operation at resonance or for broad band, below resonance operation. In electrically driven devices, it shunts the driving amplifier or other signal source requiring that the source be capable of supplying extra current. In the case of mechanically driven devices, the static capacitance acts as a load on the active part of the transducer, reducing the electrical output.

In non-resonant devices, not much can be done about the shunt capacitance, except choose a piezoelectric material having maximum activity. In resonant devices, however, the static capacitance may be "neutralized" by employing a shunt or series inductor chosen to resonate with the static capacitance at the operating frequency. This is illustrated in Fig. 23.

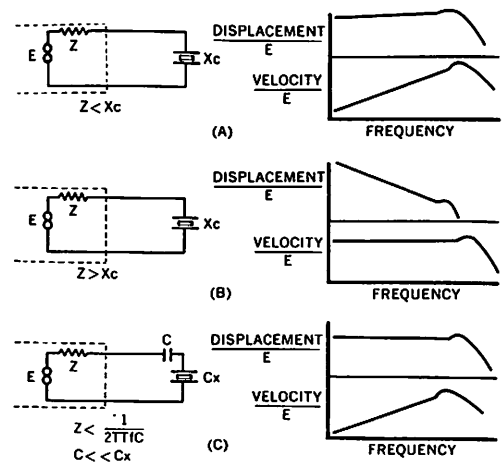



Fig. 22. Frequency Response of Non Resonant Electrically Driven Device with Different Drive Circuits.

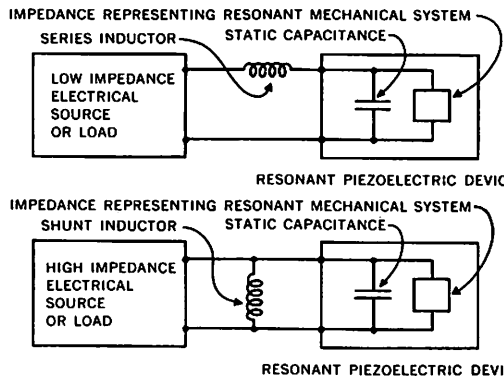



Fig. 23. Resonant Piezoelectric Device with Static Capacitance "Neutralized" by Inductor.

## PROPERTIES OF PIEZOELECTRIC MATERIALS

### Axes

Piezoelectric materials are anisotropic—their electrical, mechanical, and electromechanical properties differ for electrical or mechanical excitation along different directions. Thus for systematic tabulation of properties, we require a standardized means for identifying directions. Where crystals are concerned, we use the orthogonal axes originally assigned by crystallographers. However, we identify the axes by numerals: 1 corresponds to x axis, 2 corresponds to y axis, and 3 corresponds to z axis.

Piezoelectric ceramics are isotropic and are not piezoelectric before poling. Once they are polarized, however, they become anisotropic. The direction of the poling field is identified as the 3 direction. In the plane perpendicular to the 3 axis, the ceramics are non-directional. Accordingly, the 1 and 2 axes may be arbitrarily located but, of course, they must be perpendicular to each other.

## Elastic Constants

In order to identify the directions of stress and strain, we add two numerical subscripts to the symbol s for elastic compliance (strain/stress). The first numeral indicates the direction of stress or strain and the second numeral indicates the direction of strain or stress. The symbol s with appropriate subscripts is used ONLY to identify elastic behavior under the specific condition that all external stresses not embraced by the symbol remain constant. Thus $s_{13}$ is the symbol for the ratio of strain in the 3 direction to the stress in the 1 direction, PROVIDED there is no change in stress in the 2 and 3 directions. It also is the symbol for the ratio of strain in the 1 direction to stress in the 3 direction, PROVIDED there is no change in stress in the 1 and 2 directions.

The restriction regarding stresses in other directions deserves emphasis. Suppose that a piezoelectric plate is clamped in a vise which applies stress in the 3 direction. Now we apply stress to the plate in the 1 direction and want to calculate the resulting strain in the 1 direction. If the plate were not clamped in the vise, the stress applied along the 1 axis would cause strain in the 1 direction equal to $s_{11}$ x the applied stress. In addition there would be strain in the 2 and 3 directions. The vise, however, tends to prevent the strain in the 3 direction and in so doing, it applies stress in the 3 direction. The development of this stress violates the requirement imposed in the definition of $s_{11}$ that stresses in the 2 and 3 directions remain constant and therefore $s_{11}$ cannot be used to calculate the strain in the 1 direction.

Now consider another example. This time the plate is resting on the table and a weight is placed on top. The weight applies a stress in the 3 direction. Now we apply a stress in the 1 direction and want to calculate the resulting strain in the 1 direction. As a result of the stress applied in the 1 direction, the plate experiences strain in the 3 direction lifting the weight slightly. However, stress in the 3 direction caused by the weight has not changed (except momentarily while the weight was being lifted) and accordingly, the symbol $s_{11}$ is, in this case, appropriate for calculating the strain in the 1 direction resulting from application of stress in the 1 direction.

Shear stress or strain around the 1 axis is indicated by the subscript 4, and around the 2 axis by subscript 5, and around the 3 axis by subscript 6. Thus, $s_{44}$ is the ratio of shear strain around the 1 axis to shear stress around the 1 axis. A restriction requiring that stresses not embraced by the symbol must remain constant is theoretically applicable here also but, due to symmetry conditions it is not applicable to shear compliances of ceramics or ADP crystals.

Since piezoelectric materials interchange mechanical (elastic) and electrical energy, the elastic properties depend on electric boundary conditions. For example, when electrodes on a bar of piezoelectric material are connected together, the bar displays higher elastic compliance than when the electrodes are not connected together. Thus, in defining elastic properties, we must identify the electric boundary conditions. This is done by adding a superscript to the symbol. When the electric field across the piezoelectric body is held constant, for example by short circuiting the electrodes, we use the superscript E. When the electric charge density is held constant, for example by maintaining an open circuit at the electrodes, we use the superscript D. Thus $s_{33}^{E}$ is the symbol for the ratio strain to stress along the 3 axis under the conditions that all other external stresses are constant and the electric field is constant.

## Dielectric Constants

In piezoelectric materials the dielectric constant $\epsilon$ (dielectric displacement or charge density/electric field) depends on the directions of field and dielectric displacement; therefore we add subscripts to the symbol to indicate the directions. The first subscript denotes the direction of the electric field or dielectric displacement and the second subscript denotes the direction of the dielectric displacement or electric field. Thus $\epsilon_{33}$ is the ratio field applied in the 3 direction to the resulting dielectric displacement in the 3 direction. In most piezoelectric materials employed in transducers, a field along one axis results in dielectric displacement only along the same axis so that the two subscripts for these materials are always the same. (Of the materials discussed in this booklet, Lithium Sulphate is the only exception.) Accordingly, one subscript often is omitted, i.e. $\epsilon_3$ means $\epsilon_{33}$.

Since piezoelectric materials interchange electrical and mechanical energy, the electrical properties depend on mechanical boundary conditions. When a piezoelectric body is completely free to vibrate the dielectric constant is higher than when the body is mechanically restrained. Accordingly, superscripts are added to the symbol for dielectric constant to indicate the mechanical boundary conditions. Superscript T denotes condition of constant stress (no mechanical restraint). Superscript S denotes condition of constant strain (material completely restrained to prevent any mechanical deformation when field is applied—a condition that can be approached only under very special conditions). Thus $\epsilon_{11}^{T}$ is the dielectric constant for field and dielectric displacement in the 1 direction under the condition of constant stress on the body; and $\epsilon_{11}^{S}$ is the corresponding dielectric constant under the condition of constant strain in the body.

The relative dielectric constant, sometimes identified by the symbol K, is the ratio of absolute dielectric constant $\epsilon$ to the dielectric constant of a vacuum $\epsilon_o$ ($\epsilon_o = 8.85 \times 10^{-12}$ farads/meter).

Thus, $K_{11}^{T} = \frac{\epsilon_{11}^{T}}{\epsilon_o}$.

## Piezoelectric Constants

The electromechanical constants commonly employed are coupling k, strain constant d, and stress constant g. For each of these, the directions of field, and stress or strain are indicated by two subscripts. The first subscript indicates the direction of electric field, and the second subscript indicates the direction of stress or strain. As in the case of elastic constants, subscripts 4, 5, and 6 denote stress or strain around the 1, 2, and 3 axes respectively.

## Coupling

Coupling is an expression for the ability of a piezoelectric material to exchange electrical energy for mechanical energy or vice versa. Coupling squared is equal to the transformed energy divided by the total energy input and the same constant is applied for conversion from electrical to mechanical energy, and from mechanical to electrical energy.

Except in one special case noted below, the coupling coefficients generally used and those given in this booklet are for the cases where all external stresses (except the input stress considered in the energy transformation) are constant. Example:

$k_{31}^2$= (transformed electrical energy causing mechanical strain in the 1 direction when all external stresses are constant) ÷ (electrical energy input to electrodes on faces perpendicular to the 3 axis).

Also

$k_{31}^2$ = (transformed mechanical energy causing electrical charge to flow between connected electrodes on faces perpendicular to the 3 axis) ÷ (mechanical energy input accompanying the application of stress in the 1 direction, with all other external stresses constant).

A special case of considerable practical importance involves use of thickness vibrations in ceramic plates or discs at frequencies above the resonant frequencies determined by length and width of the element. Under these conditions, the inertia of the piezoelectric material effectively prevents lateral vibrations. The effect is the same as though infinitely rigid clamps were applied to the plate to prevent length and width vibrations. These clamps would apply opposing dynamic stresses as the element "tried" to vibrate laterally. Thus the qualification "all external stresses are constant" noted above is not met and accordingly, $k_{33}$ does not define the electromechanical coupling under these conditions. The coupling in this special case is identified by the symbol $k_t$.

Another special case is of considerable importance. It involves coupling between electric field in the 3 direction in ceramics and mechanical action simultaneously in the 1 and 2 directions. This coupling is identified by the symbol $k_p$ (planar coupling). It is important because of the ease with which it may be measured with high accuracy, yielding a simple measure of the effectiveness of poling of ceramic test specimens.

**Piezoelectric (d) Constants**

The d constants express the ratio of strain developed along or around a specified axis, to the field applied parallel to a specified axis, when all external stresses are constant. The d constants also express the ratio of short circuit charge per unit area of electrode flowing between connected electrodes which are perpendicular to a specified axis, to the stress applied along or around a specified axis, when all other external stresses are constant. Example: $d_{31}$ denotes the ratio of strain in the 1 direction to the field applied in the 3 direction when the piezoelectric material is mechanically free in all directions. It also denotes the ratio of charge per unit area of electrode which flows between electrodes which are perpendicular to the 3 axis and connected together, to the stress applied in the 1 direction, when the material is free of external stresses in all other directions.

A special case is of interest in connection with piezoelectric ceramics and Lithium Sulphate crystals. These materials develop substantial charge when subjected to equal stresses along all three axes (hydrostatic stress). The ratio of short circuit charge per unit area of electrode to the applied hydrostatic stress is identified by the symbol $d_h$ — the hydrostatic d constant. For ceramics, the electrodes are understood to be perpendicular to the 3 axis and for lithium sulphate the electrodes are understood to be perpendicular to the Y or 2 axis. A more descriptive symbol would seem to be $d_{3h}$ or $d_{2h}$, but such designations have not been adopted.

**Piezoelectric (g) Constants**

The g constants express the ratio of field developed along a specified axis to the stress applied along or around a specified axis when all other external stresses are constant. The g constants also express the ratio of strain developed along or around a specified axis to the electric charge per unit area of electrode applied to electrodes which are perpendicular to a specified axis. Example:

$g_{33}$ denotes the ratio of field developed in the 3 direction to stress applied in the 3 direction when all other external stresses are zero. It also denotes the ratio of strain developed in the 3 direction to the charge per unit area of electrode applied to electrodes on faces perpendicular to the 3 axis.

**Frequency Limitations**

An important restriction must be observed in the use of the constants discussed above to calculate the behavior of actual bodies of piezoelectric material. If the stress, strain, electric field, and dielectric displacement involved in the constants are uniform throughout the body, then the constants may be used directly in simple calculations. Example: When a static, or low frequency alternating field is applied, the change in length of a piezoelectric bar equals the appropriate d constant x applied field x length.

On the other hand, if the stress, field, etc. are not uniform throughout the body, then the behavior of the body as a whole may be determined only by integrating the behavior of all the incremental portions of the body. In this case, the various constants discussed above are used to relate stress, strain, field, charge density in each increment.

The most common situation where non-uniform distribution of stress, etc. is encountered, preventing simple bulk calculation, is when the frequency of the electrical or mechanical excitation of the body is at or close to the mechanical resonance frequency of the body.

**Frequency Constant**

Frequency constant is the product of the mechanical resonant frequency under specified electrical boundary conditions (short circuit or open circuit) and the dimension which determines that resonant frequency. It is applicable only to certain specific cases of boundary conditions. For example, $N_1$ for piezoelectric ceramics applies only to a long, thin, narrow bar polarized perpendicular to the length and measured with the polarizing electrodes connected together. The same bar poled along the length will have a different frequency constant. In this case the assigned designation $N_{3a}$ applies when measurement is made with the electrodes open circuited.

**Electrical Losses**

Some piezoelectric materials, quartz for example, are high quality dielectrics. Other piezoelectric materials, notably the piezoelectric ceramics, are relatively lossy. The dielectric losses in ceramics may be the limiting factor in the power handling capabilities of power transducers. The losses are expressed as a dissipation factor—the ratio of effective series resistance to effective series reactance. ..tan $\delta$.

**Mechanical Losses**

When an elastic body is deformed, most of the mechanical energy applied in causing the deformation is stored as elastic energy. However, a small part of the applied energy is dissipated as heat due to "molecular friction". In some applications of piezoelectric materials, such mechanical losses may become important, although usually they are far outweighed by mechanical losses in other elements of the piezoelectric device; in particular, in cement joints between piezoelectric materials and driving or driven members. Mechanical losses are expressed in terms of mechanical Q, which is the ratio of mechanical stiffness reactance or mass reactance at resonance to the mechanical resistance.

### Summary of Notations

The various notations, subscripts, and superscripts discussed above are summarized and illustrated in Table I which includes, also, notes as to limitations and special cases.

### Aging

Most of the properties of piezoelectric ceramics change gradually with time. The changes tend to be logarithmic with time after the original polarization. For example, the dielectric constant 1 hour after poling may be 1,000 and 10 hours after poling it may be 990. At 100 hours it will then be about 980, at 1000 hours about 970, and at 10,000 hours about 960. In this case, we would say that the dielectric constant ages about 1% per time decade. The aging of various properties depends on the ceramic composition and on the way the ceramic is processed during manufacturing. Exact aging rates cannot be specified. It is usual to specify that the aging of a given property will be less than some limiting rate.

Because of aging, exact values for various properties such as dielectric constant, coupling, and elastic modulus may be specified only at a stated time after poling. It should be obvious that the longer the time period that is allowed after poling, the more stable the material becomes.

### High Stresses

Most of the properties of piezoelectric ceramics vary with the level of electrical or mechanical stress when such stresses are large. A similar situation exists for some of the properties of Rochelle salt crystal between about −18°C and +24°C. Data commonly presented for piezoelectric ceramics and crystals are for stress levels sufficiently low for the results to be independent of stress. Specific data are presented later in this booklet for high stress operation of ceramics.

### Curie Point

For each piezoelectric ceramic there is a characteristic temperature called the Curie Point. When a ceramic element is heated above the Curie Point, it suffers permanent and complete loss of piezoelectric activity. Thus, for any ceramic the Curie Point is the absolute maximum temperature. In practice, the operating temperature must be limited to some value substantially below the Curie Point because at elevated temperatures the aging process is accelerated, electrical losses increase, and the maximum safe stress is reduced.

Rochelle Salt crystal has two Curie Points; approximately −18°C and +24°C, but does not suffer permanent loss of activity when these temperatures are exceeded.

### Units

In this booklet and in most modern texts and papers, the electrical, mechanical, and electromechanical properties of piezoelectric materials are expresses in rationalized mks units. The reader is urged to resist the temptation to convert any of the constants to other units. Experience has shown that conversion leads to errors and confusion. An example will illustrate. From Tables II and III, for PZT-5A, we find that

$$g_{33} = 24.8 \times 10^{-3} \frac{\text{volts/meter}}{\text{Newtons/meter}^2} = 24.8 \times 10^{-3} \frac{\text{meters/meter}}{\text{Coulombs/meter}^2}$$

The first expression indicates the open circuit voltage developed for a given mechanical drive. The second expression indicates the mechanical deformation resulting from a given electrical drive. They are numerically identical.

Now, let's convert the mechanical parts of these expressions to the cgs system but keep the electrical units unchanged.

$$24.8 \times 10^{-3} \frac{\text{volts/meter}}{\text{Newton/meter}^2} = 24.8 \times 10^{-6} \frac{\text{volts/cm}}{\text{dyne/cm}^2}$$

$$24.8 \times 10^{-3} \frac{\text{meter/meter}}{\text{Coulomb/meter}^2} = 24.8 \times 10^{1} \frac{\text{cm/cm}}{\text{Coulomb/cm}^2}$$

Note that now the mechanical to electrical constant is numerically different from the electrical to mechanical constant, the ratio being $10^7$. Aside from the complication of dealing with twice as many constants when using cgs mechanical units we have the question of how to deal with a transducer design that involves both electrical to mechanical and mechanical to electrical conversion.

**Use and Measurement of Constants**

Most of the constants discussed above are MATERIAL constants. Except in a few special cases, they cannot be used in any simple manner to determine EXACT behavior of plates, discs, cylinders, etc. as used in practical applications. For example, consider the problem of calculating the low frequency, open circuit sensitivity of the compression accelerometer of Fig. 9. For this purpose, the device may be considered to be a rigid body so that all parts experience the same acceleration. Thus, when the device is subjected to acceleration ($a$) in the direction shown (perpendicular to the faces of the piezoelectric disc; i.e. the 3 direction), the mass M experiences the acceleration ($a$). From elementary principles we know that the force acting on the mass is $F = Ma$.

From the construction of the device, it is obvious that the force F causing acceleration of the mass is applied to the piezoelectric disc in the 3 direction.

Now, if we assume that no other forces act on the ceramic discs, we may calculate the sensitivity as follows:

By definition

$$g_{33} = \frac{\text{field developed in 3 direction}}{\text{stress applied in 3 direction}}$$

(all other external stresses constant)

For the accelerometer discs

$$g_{33} = \frac{\text{Voltage developed/thickness}}{\text{Force applied/electrode area}}$$

Now substituting $F = Ma$ and rearranging

$$\frac{\text{voltage developed}}{a} = M\, g_{33} \frac{\text{thickness}}{\text{area}} = \text{Sensitivity}$$

The sensitivity so calculated is an approximation chiefly because of the assumption that the only force acting on the discs is the force required to accelerate the mass. There are, in fact, other forces of significant value acting on the discs.

When compressive force is applied to the piezoelectric disc in the thickness direction, the disc tends to expand radially due to natural elastic behavior. However, the discs are "attached" to the mass and to the supporting base by adhesives or by frictional engagement. Therefore, the natural tendency toward radial expansion under thickness compression is interfered with by the radial stiffness of the mass and the base. This results in reduced sensitivity. If the restraint were complete, the sensitivity would be reduced to about ⅔ of the calculated value (based on PZT-5).

To make accurate determinations of the various constants, it is necessary to perform measurements on test specimens which are proportioned to minimize undesirable effects such as the radial stress effect in the above illustration. The necessary proportions of test specimens and the measurements and calculations required

to yield accurate data are detailed in "IRE Standards on Piezoelectric Crystals, 1961, Proc. IRE, pp. 1162-1169, July, 1961" and Clevite bulletin "Measuring Properties of Piezoelectric Ceramics".

### Specific Properties of Piezoelectric Ceramics

Piezoelectric ceramics commercially available from the Piezoelectric Division, Clevite Corporation include Ceramic B, PZT-4, PZT-5A, PZT-5H, and PZT-8.

Ceramic B is a modified Barium Titanate which offers improved temperature stability and lower aging in comparison with unmodified Barium Titanate.

"PZT" is a registered trademark employed by Clevite to identify a family of Lead Zirconate—Lead Titanate compositions.

PZT-4 is used for high power acoustic radiating transducers because of its high resistance to depolarization and low dielectric losses under high electric drive. Its high resistance to depolarization under mechanical stress makes it suitable for use in deep-submersion accoustic transducers and as the active element in electrical power generating systems.

PZT-5A has high sensitivity, high time stability, and resistivity at elevated temperatures. It is used in hydrophones and instrument applications.

PZT-5H has higher sensitivity and higher dielectric constant than PZT-5A and is in most other respects similar to PZT-5A. Its markedly lower Curie point, however, limits the working temperature range and leads to lower temperature stability.

PZT-8 is a high power material generally similar to PZT-4 but it has much lower dielectric losses under high electric drive and has greater resistance to depolarization. PZT-8 has somewhat lower dielectric constant and coupling.

Comparison of the above materials at room temperature may be made roughly using the table below, with the material with the highest value rated 100% and the others in proportion. For more exact comparison, refer to the detailed tables which follow.

| | Cer. B | PZT-4 | PZT-5A | PZT-5H | PZT-8 |
|---|---|---|---|---|---|
| | % of Highest Rated Ceramic | | | | |
| Coupling | 51 | 89 | 92 | 100 | 77 |
| Short circuit sensitivity ($d_{33}$) | 25 | 49 | 63 | 100 | 36 |
| Open circuit sensitivity ($g_{33}$) | 54 | 100 | 95 | 75 | 94 |
| Relative dielectric constant, free ($\epsilon_{33}^T/\epsilon_O$) | 35 | 38 | 50 | 100 | 29 |
| Compliance ($S_{33}^E$) | 44 | 75 | 91 | 100 | 67 |
| Field for dissipation factor = 4% | 17 | 40 | 5 | 3 | 100 |
| Strain (non resonant) @ field for dissipation factor = 4% | 12 | 54 | 8 | 8 | 100 |
| Mechanical Q | 40 | 50 | 8 | 7 | 100 |
| Curie Point | 115°C | 328°C | 365°C | 193°C | 300°C |
| Approximate maximum operating temperature | 70°C | 200°C | 250°C | 125°C | 175°C |

Specific data for these ceramics are given in Tables II to VI incl.

Table II describes the symbols and units used in succeeding tables.

Table III lists room temperature, low signal data. These properties are subject to some fluctuations from piece to piece, and from batch to batch.

Table IV gives data relating to temperature and time stability. Data for the former are for samples subjected to an appropriate temperature stabilizing treatment*. This treatment reduces markedly temperature hysteresis effects and causes a relatively small decrease in piezoelectric coupling and increase in dielectric constant. Temperature hysteresis of Ceramic B is, however, not eliminated by any known stabilizing treatment. Data shown for Ceramic B are for increasing temperature only, and changes at the transition are more extreme with decreasing temperature.

Aging data are listed as % change per time decade. These changes tend to be linear as function of the log of time, but there are significant deviations from this behavior.

Table V lists high signal properties, including data for both mechanical and electric driving conditions. These data allow comparison of the several compositions with respect to use in acoustic radiating transducers or in high voltage electrical generating systems. For acoustic radiating transducers important criteria are values of tan $\delta$ and change of permittivity with electric drive, change of permittivity and sensitivity with mechanical bias, allowable mechanical bias, dynamic strength, and dependence of mechanical Q on dynamic stress. For electrical generating systems, the limiting factor is the maximum compressive stress (cycled) which may be maintained without significant degradation.

With acoustic receivers, even though these are not high signal devices, several properties listed in Table V are significant, since hydrophones are often operated at great depth in the ocean and there is therefore a significant mechanical bias stress. Cycling effects may be important if the hydrophone is to be submerged repeatedly.

Table VI lists data related to thermal effects, including pyroelectric constants, thermal expansion, thermal conductivity, and heat capacity. The pronounced effects of temperature stabilization on thermal expansion and pyroelectric constants are shown.

Figures 26 through 31 which precede the tables at the end of this booklet show variation of $\epsilon_{33}^{T}$, $k_p$, $g_{31}$, $d_{31}$, $N_1$, and $Q_m$ with temperature for the various ceramics. The curves for PZT-5A and PZT-4 hold only after temperature stabilization.

**Specific Properties of Piezoelectric Crystals**

Piezoelectric crystals commercially available from the Piezoelectric Division, Clevite Corporation include Rochelle salt, ammonium dihydrogen phosphate (ADP), and lithium sulphate.

Rochelle salt is used principally in "Bimorphs" in phonograph pickups, microphones, and headphones, offering the advantage of higher sensitivity than is available from ceramic "Bimorphs."

ADP has much lower coupling than Rochelle salt but offers the advantage of very high stability over a wide temperature range. It is used in underwater sound applications and in instruments such as accelerometers.

Lithium sulphate has a large hydrostatic piezoelectric effect which makes it useful in measurement applications such as sound pressure measuring devices. It also has a strong thickness ex-

*This treatment is not ordinarily applied to production pieces, and is actually recommended only for PZT-4, PZT-5A and PZT-8. With PZT-4 and PZT-8, the treatment consists of a one-hour soak at 200° C. The stabilizing treatment for PZT-5A consists of a 15-second soak at 250° C in oil followed by a 60-second soak in room temperature oil, with the process repeated at least five times. The resulting decrease in coupling and increase in dielectric constant are about 10% or less.

pansion effect and a favorable acoustic impedance which lead to its use in ultrasonic applications.

Specific data for these crystals are given in Table VII and Figs. 32 and 33 which precede the tables.

## PROPERTIES OF PIEZOELECTRIC ELEMENTS

### Equivalent Circuits

Equivalent circuit techniques have been utilized for many years to obtain solutions to electrical and mechanical problems. Subsequently, it was realized by Mason[1], [2] that these same techniques could be used to describe the behavior of piezoelectric elements. Indeed, for most engineering purposes, the equivalent circuit description of electro-mechanical transducers is at once simple and adequate.

Of the available analogies which may be used in the construction of equivalent circuits for electro-mechanical systems, it is expedient to choose, for piezoelectric structures, that exhibited in the table below:

| Electrical Unit | Analogous Mechanical Unit |
|---|---|
| Voltage | Force |
| Current | Velocity |
| Charge | Displacement |
| Capacitance | Compliance |
| Inductance | Mass |
| Impedance | Mechanical Impedance |

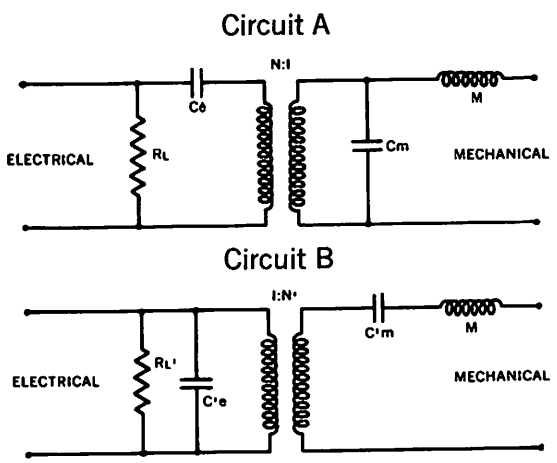



Fig. 24. Basic Equivalent Circuits.

The equivalent circuits chosen as basic in this booklet are the two shown in Fig. 24. If the constants in these two circuits are suitably related, the circuits are equivalent at all frequencies. The mechanical terminals represent the face or point of mechanical energy transfer to or from the piezoelectric element. The inductance symbol represents the effective vibrating mass of the element. The transformer symbol represents an ideal electromechanical transformer—a device that transforms voltage to force and vice versa, and current to velocity and vice versa, without loss and without energy storage. The transformation ratio N:1 in the circuit A is the ratio of voltage input to force output of the ideal transformer and also the ratio of velocity input to current output. It is used in calculations just as the turns ratio of an ideal transformer is used in purely electrical network calculations. The tranformation ratio 1:N' in the circuit B has similar significance. The capacitance symbols on the electrical side represent electrical capacitances. The capacitance symbols on the mechanical side represent mechanical compliances.

The choice of circuit for any particular problem depends on the external circuit elements connected to the piezoelectric element. Since the two circuits are equivalent, either may be used, but often one will be more convenient than the other. For example, if the electrical terminals are connected to a constant current generator and we wish to calculate the force applied to a mechanical load connected to the mechanical terminals of the piezoelectric element, the problem is simplified by selection of circuit A because this eliminates capacitance Ce from the calculations.

1. Mason, W. P. An Electromechanical Representation of a Piezoelectrical Crystal used as a Transducer, Proc I.R.E. 23 Oct. 1935 pp. 1252-63.
2. Mason, W. P. Electromechanical Transducers and Wave Filters. 2nd Edition. D. Van Nostrand, New York, 1948.

These circuits are quite adequate for most design purposes. However, it should be pointed out that they only approximate the actual behavior of the piezoelectric elements they are intended to represent. The approximation is useful up to and slightly above the first resonance frequency of the mounted but unloaded element. At higher frequencies, further resonances generally may be observed in the behavior of a piezoelectric element due to the distributed nature of the mass, compliance, etc., for which in the equivalent circuits considered in this bulletin, only lumped elements are used. Better approximations of the actual performance can be obtained by modifying the equivalent circuits to include additional reactance elements, or by allowing some elements of the "simple" circuits to vary with frequency in a prescribed manner.

The above modifications are seldom used in practice due to the additional complexity involved in analyzing the behavior and the minor benefits usually obtained. For these reasons, no further details are given here.

Due to the approximate nature of the equivalent circuits previously discussed, the accuracy of representation of the piezoelectric element is better at some frequencies than at others. The frequency range of most accuracy depends on the choice of values assigned to the elements of the circuit. For the purposes fo the following tables, the capacitances, transducer ratios, and compliances have been selected to provide accurate representation of the crystal element at low frequencies up to about one-half the resonance frequency of the mounted but unloaded crystal element. The effective mass, or moment of inertia, however, is chosen so that the equivalent circuit will have the same resonant frequency as the actual crystal. Fig. 25 shows the actual measured response of a three-corner mounted Rochelle salt twister "Bimorph," together with the response computed from the equivalent circuit using data from Fig. 34 at the end of this booklet.

Fig. 25 also illustrates another point to be considered in employing the equivalent circuits. The height of the actual measured resonance peak of the crystal element is finite, due to various mechanical losses in the element. The equivalent circuit data, however, includes no mechanical loss element, so that the computed response is infinite at resonance.

For most "non resonant" electromechanical transducer design problems, this omission is not significant as losses introduced, usually deliberately for control of frequency response, greatly outweigh the internal losses, making consideration of the latter nothing but a burden.

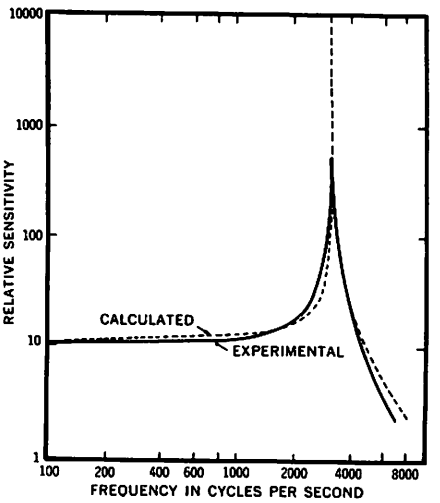


Fig. 25. Sensitivity of Twister "Bimorph"—calculated and experimental.

**Equivalent Circuit Data for "Bimorphs" and "Multimorphs"**

Equivalent circuit data for "Bimorphs" and "Multimorphs" are given in Figs.34, 35, 36, and 37 at the end of this booklet. These data are based on measurements on large numbers of elements performed in the laboratory of the Piezoelectric Division. Great care was taken to provide close to ideal mounting and driving conditions. Thus, it should be expected that in practical devices, performance will differ somewhat from the performance predicted from the data in the Figures.

The equivalent circuit constants given in Figs. 34-37 are expressed in units as indicated below:

$C_e$; $C'_e$ = electrical capacitance in farads

N = electro-mechanical linear transducer ratio in volts/newton, or meters/coulomb

N' = electro-mechanical linear transducer ratio in newtons/volt or coulomb/meter

$N_\theta$ = electro-mechanical torsional transducer ratio in volts/newton-meter or radians/coulomb

$C_m$; $C'_e$ = mechanical compliance in meters/newton

$C_\theta$ = torsional compliance in radians/newton-meter

M = effective mass in kilograms

$I_\theta$ = effective moment of inertia in kilogram-meters$^2$

It will be noted that the values of capacitance are given for Rochelle salt elements at a temperature of 30° Centrigrade. The capacitance of Rochelle salt varies strongly with temperature. A correction curve of percent of 30° capacitance over a temperature range of 0 to 40°C is shown in Fig. 32. Below the peak of this curve, which is at approximately 25°C, the capacitance of Rochelle salt is also somewhat voltage sensitive. For this reason, the values shown are for a low field, which would correspond, for example, to a volt or a fraction of a volt, applied to a "Bimorph."

The elements of the equivalent circuits for ceramic "Bimorphs" and "Multimorphs" vary with dimensions in a complex manner due to the influence of the metal vanes sandwiched between the ceramic plates of the "Bimorphs" and due to the longitudinal holes through the "Multimorphs." The data in figures 36 and 37 are valid only for elements of the types used in phonograph cartridges—for "Bimorph" thickness in the range of .018" to .026" and "Multimorph" thickness in the range of .024" to .028".

**Properties of Ceramic Tubes**

Piezoelectric ceramic tubes are used extensively in underwater sound transducers. One large application is in omnidirectional hydrophones. Fig. 11 illustrates a simple design. Numerous variations are possible. For example, the electrodes may cover the cylindrical surfaces, with polarization in the thickness direction as shown in Fig. 11. In another arrangement, the electrodes may cover the ends of the tube, with polarization in the length direction. In a third arrangement, the tube may be cut length-wise into an even number of curved plates. Electrodes may then be applied to the cut edges. Following this, the individual plates are polarized and the cylinder is reassembled.

For any of the electrode and polarization arrangements, several possibilities exist for subjecting selected areas of the tube to the sound field. Generally, the inner surface is shielded from the sound field either by lining the surface with acoustic decoupling material, or by providing end caps as shown in Fig. 11. When end caps are not provided, the ends of the tube may or may not be exposed to the sound field.

The open circuit electroacoustic sensitivities for various electrode and polarization arrangements and for various acoustic coupling arrangements are shown in Figs. 38, 39, and 40 for Ceramic B, PZT-4, PZT-5, and PZT-5H. The curves are based on publications by Langevin[3] and Germano[4]. They are applicable only for frequencies which are well below the lowest mechanical resonance of the tube and which have wave lengths in the water large' compared with the largest dimension of the tube.

[3]"The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes" by R. A. Langevin, The Journal of The Acoustical Society of America, Vol. 26, No. 3, 421-427, May, 1954.
[4]"Supplement to: The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes, by R. A. Langevin", The Journal of the Acoustical Society of America, Vol. 34, No. 8, 1139-1141, August, 1962.

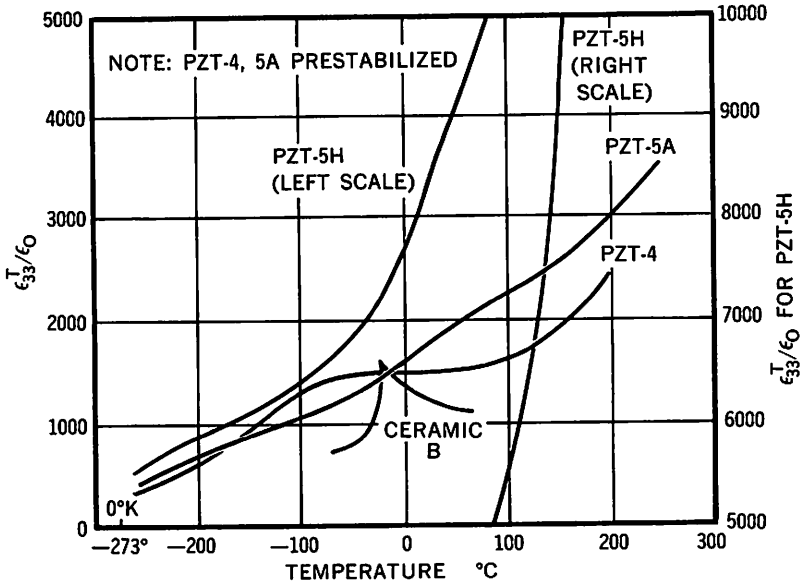



Fig. 26. Relative Dielectric Constant vs. Temperature— Piezoelectric Ceramics.

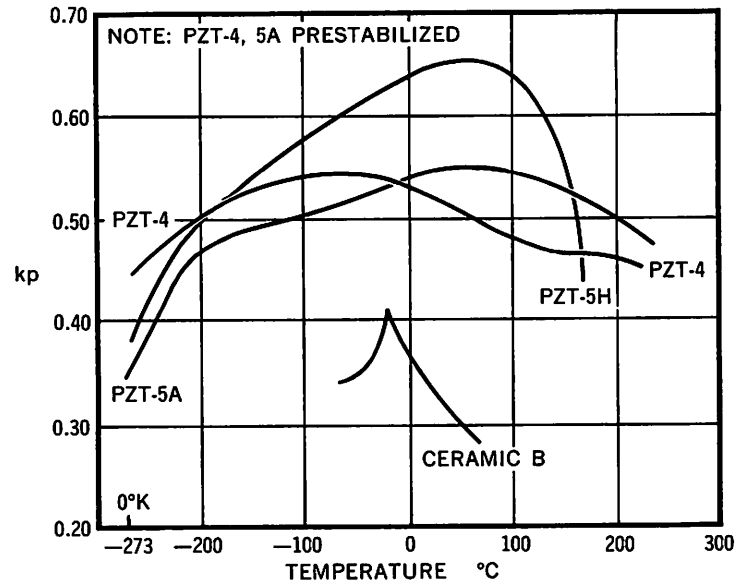



Fig. 27. Planar Coupling Factor vs. Temperature— Piezoelectric Ceramics.

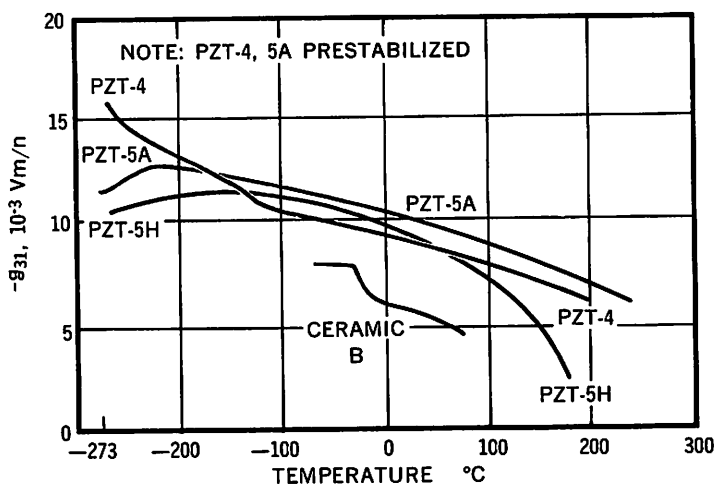



Fig. 28. $g_{31}$ vs. Temperature—Piezoelectric Ceramics.

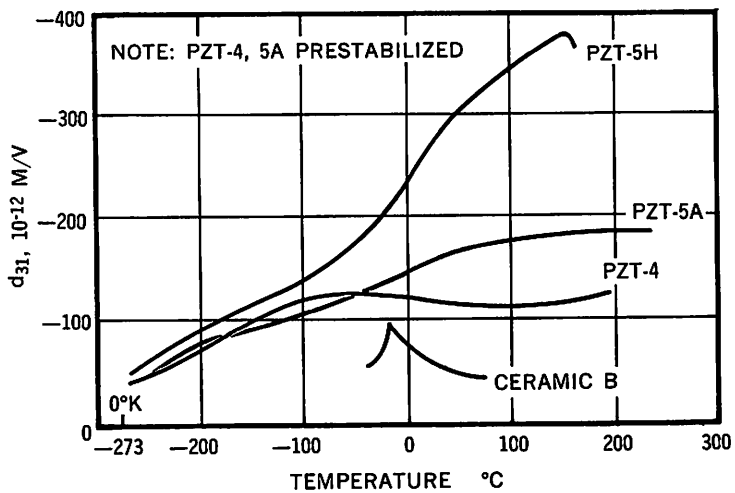



Fig. 29. $d_{31}$ vs. Temperature—Piezoelectric Ceramics.

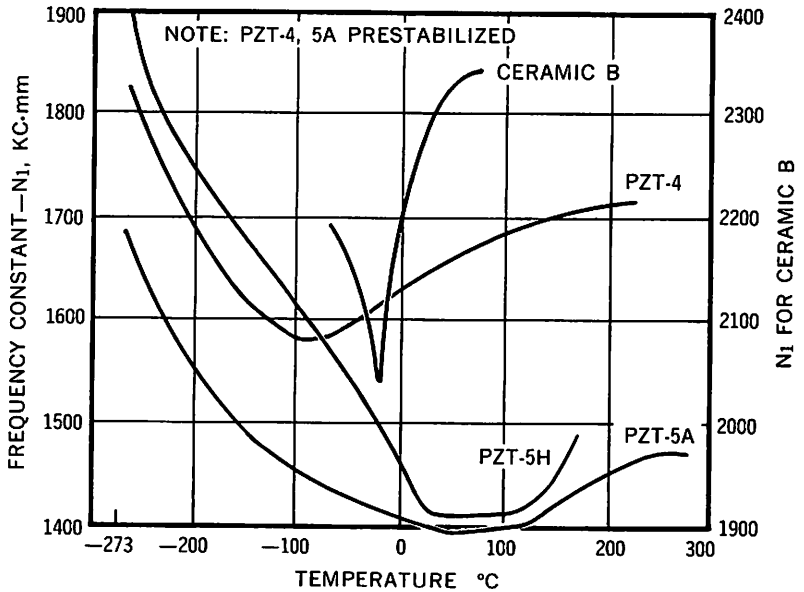



Fig. 30. Frequency Constant vs. Temperature—Piezoelectric Ceramics.

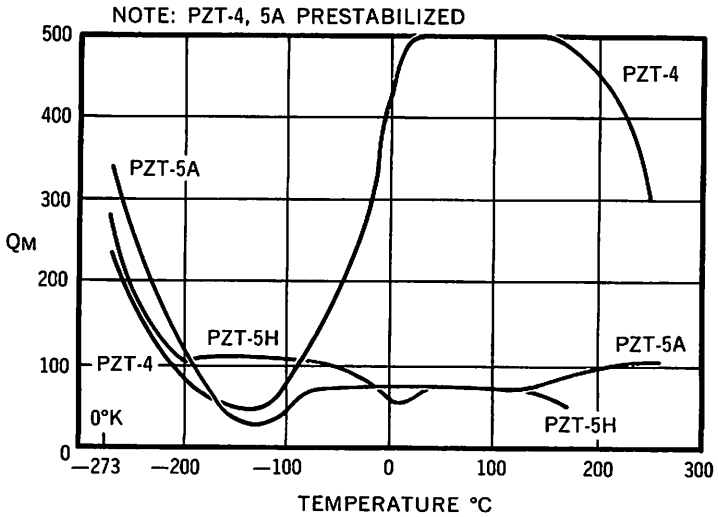



Fig. 31. Mechanical Q vs. Temperature—Piezoelectric Ceramics.

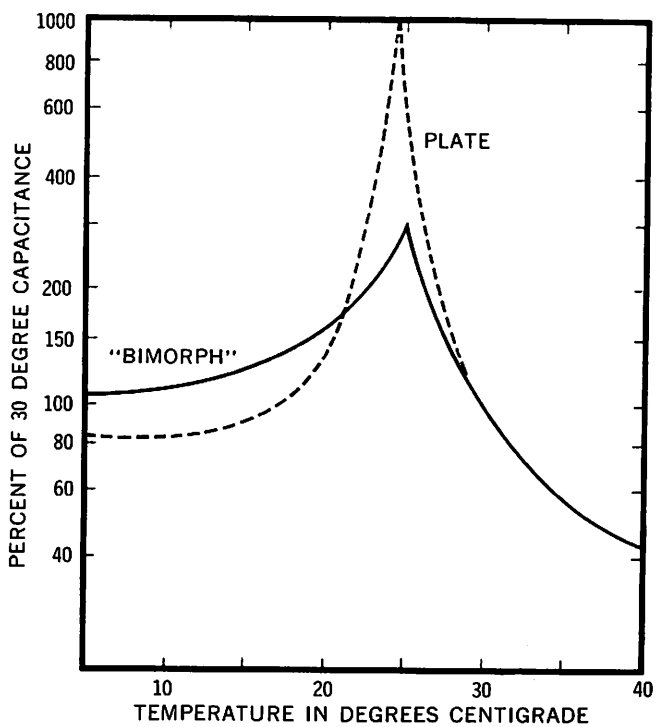



Fig. 32. Capacitance vs. Temperature-Rochelle Salt

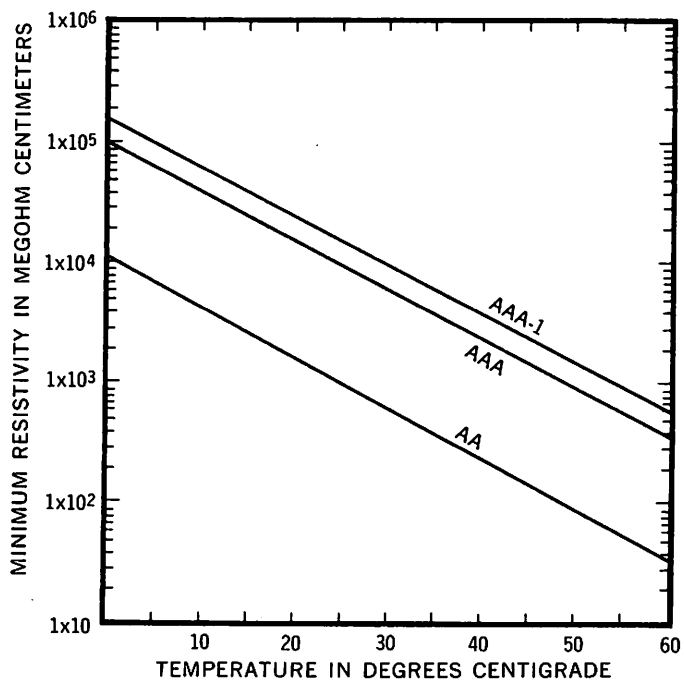
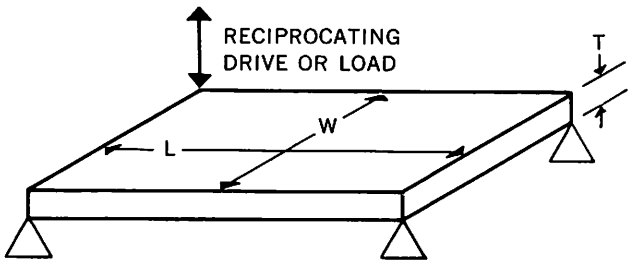
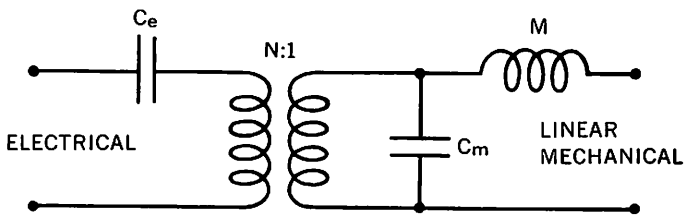


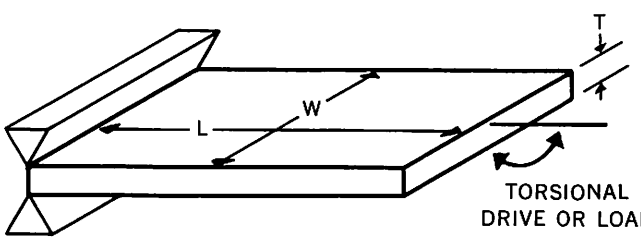

Fig. 33. Resistivity vs. Temperature – ADP

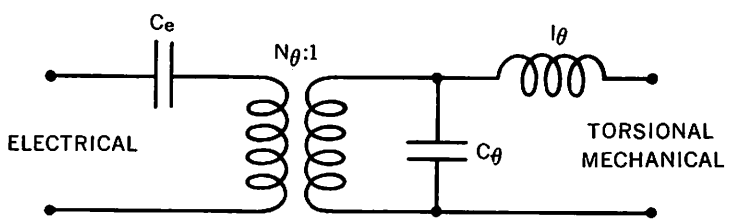



L, W, T....Inches

| Parallel | | | | Series | |
|---|---|---|---|---|---|
| **Ce 30°C *** | **N** | **Cm** | **M** | **Ce 30°C *** | **N** |
| Picofarads | Volts/Newton or Meters/Coulomb | Meters/Newton | Kg | Picofarads | Volts/Newton or Meters/Coulomb |
| $300\frac{LW}{T}$ | $\frac{5.6}{T}$ | $1.1 \times 10^{-8}\frac{LW}{T^3}$ | $4.3 \times 10^{-3}$ LWT | $75\frac{LW}{T}$ | $\frac{11}{T}$ |

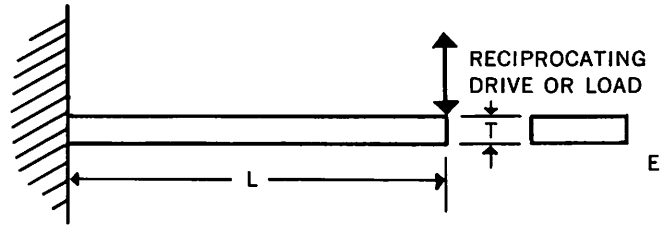



L, W, T....Inches

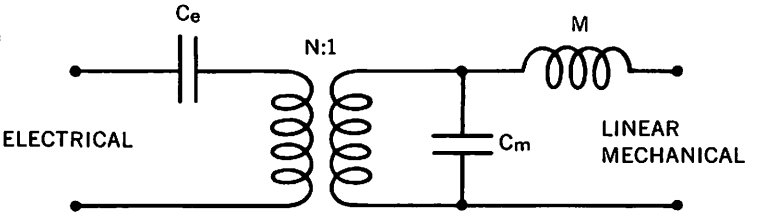
| Parallel | | | | Series | |
|---|---|---|---|---|---|
| **Ce 30°C *** | **Nθ** | **Cθ** | **Iθ** | **Ce °30C *** | **Nθ** |
| Picofarads | Volts/Newton-Meter or Radians/Coulomb | Radians/Newton-Meter | Kg-meter$^2$ | Picofarads | Volts/Newton-Meter or Radian/Coulomb |
| $300\frac{LW}{T}$ | $\frac{220}{WT}$ | $17 \times 10^{-6}\frac{L}{WT^3}$ | $7.0 \times 10^{-7}$ LW$^3$T | $75\frac{LW}{T}$ | $\frac{440}{WT}$ |

Fig. 34 Rochelle Salt Torque Bimorph Equivalent Circuit Data.
*Capacitance Ce Varies strongly with Temperature — See Fig. 32

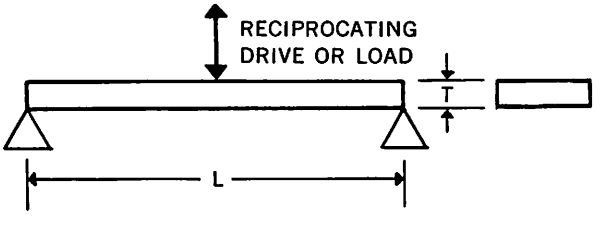



CANTILEVER
MOUNTING

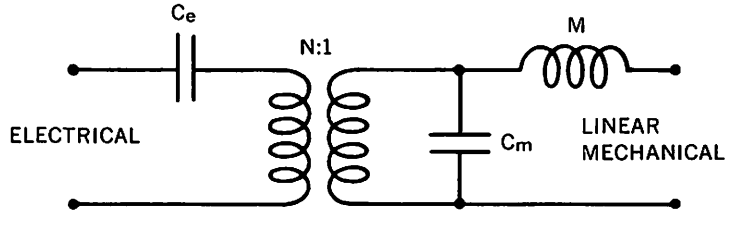
L, W, T.....Inches




| Parallel | | | | Series | |
|---|---|---|---|---|---|
| **Ce 30°C *** | **N** | **Cm** | **M** | **Ce 30°C *** | **N** |
| Picofarads | Volts/Newton or Meters/Coulomb | Meters/Newton | Kg | Picofarads | Volts/Newton or Meters/Coulomb |
| $300\frac{LW}{T}$ | $2.9\frac{L}{WT}$ | $7.0 \times 10^{-9}\frac{L^3}{WT^3}$ | $6.7 \times 10^{-3}$ LWT | $75\frac{LW}{T}$ | $5.8\frac{L}{WT}$ |

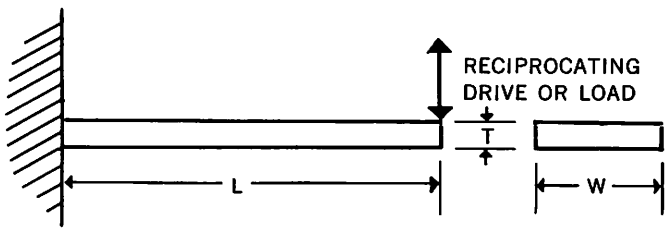



L, W, T.....Inches

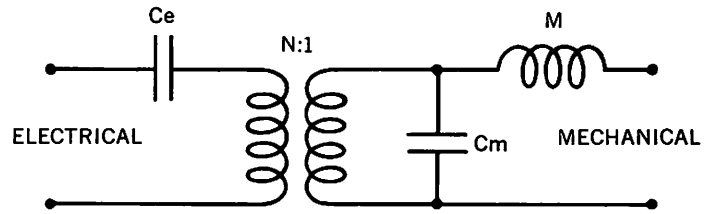



| Parallel | | | | Series | |
|---|---|---|---|---|---|
| **Ce 30°C *** | **N** | **Cm** | **M** | **Ce 30°C *** | **N** |
| Picofarads | Volts/Newton or Meters/Coulomb | Meters/Newton | Kg | Picofarads | Volts/Newton or Meters/Coulomb |
| $300\frac{LW}{T}$ | $0.73\frac{L}{WT}$ | $4.40 \times 10^{-10}\frac{L^3}{WT^3}$ | 13 LWT | $75\frac{LW}{T}$ | $1.5\frac{L}{WT}$ |

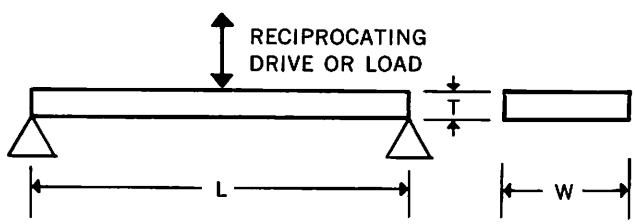
Fig. 35 Rochelle Salt Bender Bimorph Equivalent Circuit Data.
*Capacitance Ce varies strongly with Temperature—See Fig. 32.



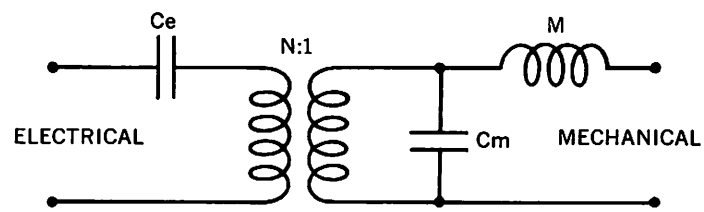

L, W, T....Inches




| TYPE | Parallel | | | | Series | |
|---|---|---|---|---|---|---|
| | Ce | N | Cm | M | Ce | N |
| | Picofarads | Volts/Newton or Meters/Coulomb | Meters/Newton | Kg | Picofarads | Volts/Newton or Meters/Coulomb |
| PZT5B Bimorph | $2000\frac{LW}{T}$ | $.3\frac{L}{WT}$ | $2.8 \times 10^{-9}\frac{L^3}{WT^3}$ | .033LWT | $500\frac{LW}{T}$ | $.6\frac{L}{WT}$ |
| PZT5H Bimorph | $2700\frac{LW}{T}$ | $.25\frac{L}{WT}$ | $2.4 \times 10^{-9}\frac{L^3}{WT^3}$ | .033LWT | $670\frac{LW}{T}$ | $.5\frac{L}{WT}$ |
| PZT5HN Bimorph | $3800\frac{LW}{T}$ | $.25\frac{L}{WT}$ | $2.8 \times 10^{-9}\frac{L^3}{WT^3}$ | .03LWT | $950\frac{LW}{T}$ | $.5\frac{L}{WT}$ |
| PZT5B Multimorph | | | $3.6 \times 10^{-9}\frac{L^3}{WT^3}$ | .025LWT | $470\frac{LW}{T}$ | $.6\frac{L}{WT}$ |
| PZT5H Multimorph | | | $3.0 \times 10^{-9}\frac{L^3}{WT^3}$ | .025LWT | $730\frac{LW}{T}$ | $.5\frac{L}{WT}$ |

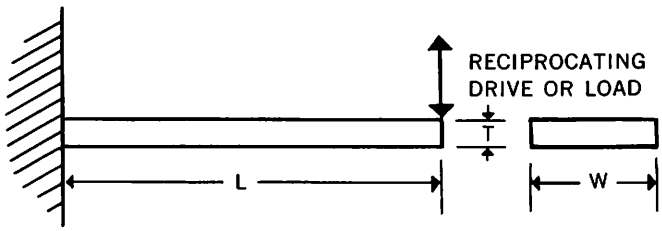



L, W, T....Inches

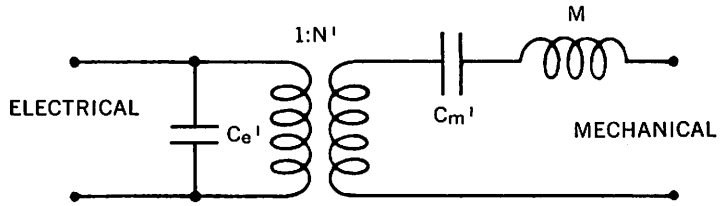



| TYPE | Parallel | | | | Series | |
|---|---|---|---|---|---|---|
| | Ce | N | Cm | M | Ce | N |
| | Picofarads | Volts/Newton or Meters/Coulomb | Meters/Newton | Kg | Picofarads | Volts/Newton or Meters/Coulomb |
| PZT5B Bimorph | $2000\frac{LW}{T}$ | $.075\frac{L}{WT}$ | $.17 \times 10^{-9}\frac{L^3}{WT^3}$ | .065LWT | $500\frac{LW}{T}$ | $.15\frac{L}{WT}$ |
| PZT5H Bimorph | $2700\frac{LW}{T}$ | $.063\frac{L}{WT}$ | $.15 \times 10^{-9}\frac{L^3}{WT^3}$ | .065LWT | $670\frac{LW}{T}$ | $.13\frac{L}{WT}$ |
| PZT5HN Bimorph | $3800\frac{LW}{T}$ | $.063\frac{L}{WT}$ | $.17 \times 10^{-9}\frac{L^3}{WT^3}$ | .060LWT | $950\frac{LW}{T}$ | $.13\frac{L}{WT}$ |
| PZT5B Multimorph | | | $.23 \times 10^{-9}\frac{L^3}{WT^3}$ | .050LWT | $470\frac{LW}{T}$ | $.15\frac{L}{WT}$ |
| PZT5H Multimorph | | | $.18 \times 10^{-9}\frac{L^3}{WT^3}$ | .050LWT | $730\frac{LW}{T}$ | $.13\frac{L}{WT}$ |

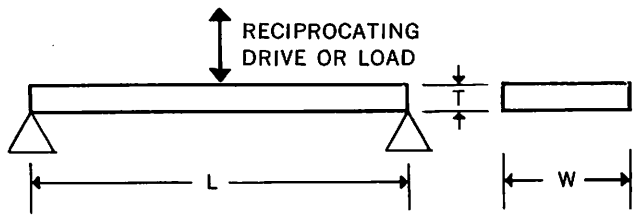
Fig. 36 Ceramic Bender Bimorph and Multimorph Approximate Equivalent Circuit Data.



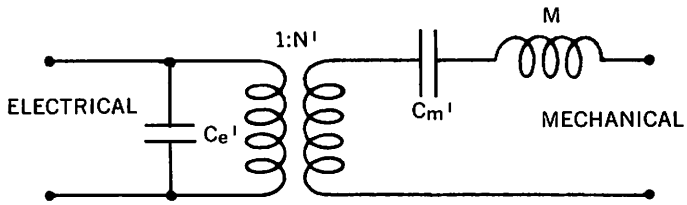

L, W, T.....Inches




| TYPE | Parallel | | | | Series | |
|---|---|---|---|---|---|---|
| | Ce' | N' | Cm' | M | Ce' | N' |
| | Picofarads | Newtons/Volt or Coulombs/Meter | Meters/Newton | Kg | Picofarads | Newtons/Volt or Coulombs/Meter |
| **PZT5B Bimorph** | $1900\frac{LW}{T}$ | $.14\frac{WT}{L}$ | $2.9 \times 10^{-9}\frac{L^3}{WT^3}$ | .033LWT | $470\frac{LW}{T}$ | $.07\frac{WT}{L}$ |
| **PZT5H Bimorph** | $2600\frac{LW}{T}$ | $.19\frac{WT}{L}$ | $2.5 \times 10^{-9}\frac{L^3}{WT^3}$ | .033LWT | $650\frac{LW}{T}$ | $.095\frac{WT}{L}$ |
| **PZT5HN Bimorph** | $3600\frac{LW}{T}$ | $.23\frac{WT}{L}$ | $3.0 \times 10^{-9}\frac{L^3}{WT^3}$ | .030LWT | $900\frac{LW}{T}$ | $.12\frac{WT}{L}$ |
| **PZT5B Multimorph** | | | $3.8 \times 10^{-9}\frac{L^3}{WT^3}$ | .025LWT | $640\frac{LW}{T}$ | $.076\frac{WT}{L}$ |
| **PZT5H Multimorph** | | | $3.2 \times 10^{-9}\frac{L^3}{WT^3}$ | .025LWT | $460\frac{LW}{T}$ | $.11\frac{WT}{L}$ |

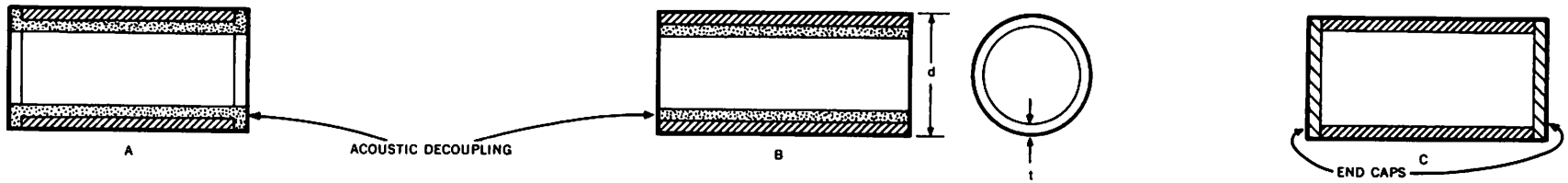


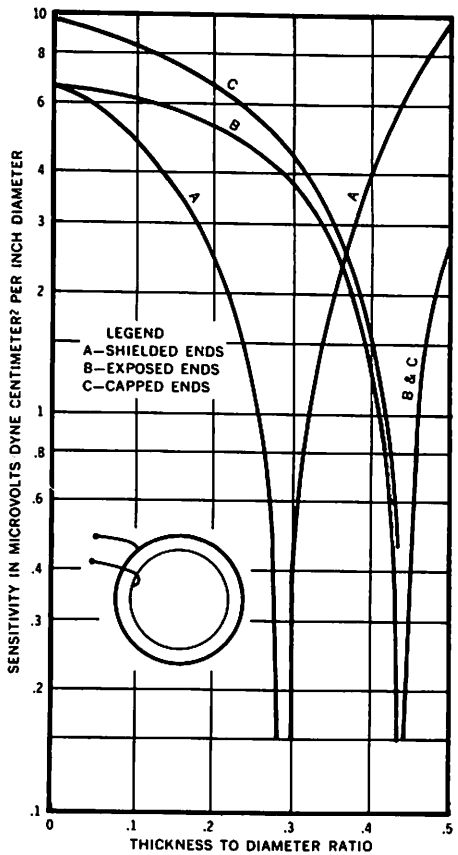

L, W, T.....Inches

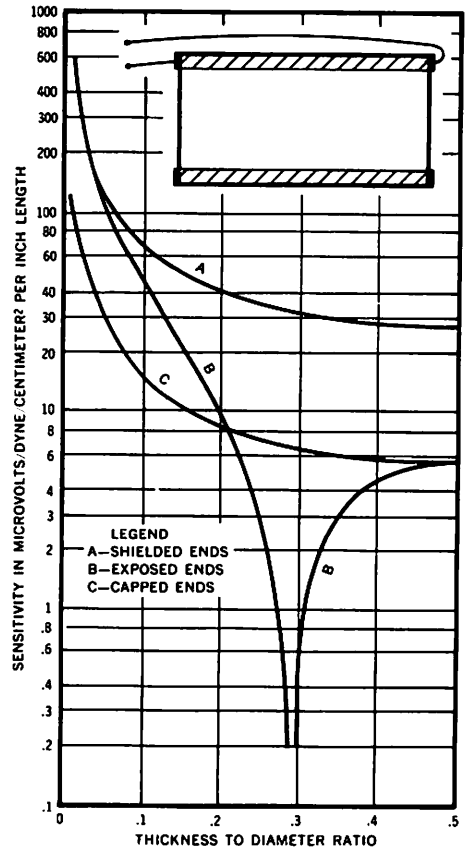



| TYPE | Parallel | | | | Series | |
|---|---|---|---|---|---|---|
| | Ce' | N' | Cm' | M | Ce' | N' |
| | Picofarads | Newtons/Volt or Coulombs/Meter | Meters/Newton | Kg | Picofarads | Newtons/Volt or Coulombs/Meter |
| **PZT5B Bimorph** | $1900\frac{LW}{T}$ | $.58\frac{WT}{L}$ | $.18\frac{L^3}{WT^3}$ | .065LWT | $470\frac{LW}{T}$ | $.29\frac{WT}{L}$ |
| **PZT5H Bimorph** | $2600\frac{LW}{T}$ | $.75\frac{WT}{L}$ | $.16\frac{L^3}{WT^3}$ | .065LWT | $650\frac{LW}{T}$ | $.38\frac{WT}{L}$ |
| **PZT5HN Bimorph** | $3600\frac{LW}{T}$ | $.92\frac{WT}{L}$ | $.18\frac{L^3}{WT^3}$ | .060LWT | $900\frac{LW}{T}$ | $.46\frac{WT}{L}$ |
| **PZT5B Multimorph** | | | $.24\frac{L^3}{WT^3}$ | .050LWT | $640\frac{LW}{T}$ | $.30\frac{WT}{L}$ |
| **PZT5H Multimorph** | | | $.20\frac{L^3}{WT^3}$ | .050LWT | $460\frac{LW}{T}$ | $.46\frac{WT}{L}$ |

Fig. 37 Ceramic Bender Bimorph and Multimorph Approximate Equivalent Circuit Data.



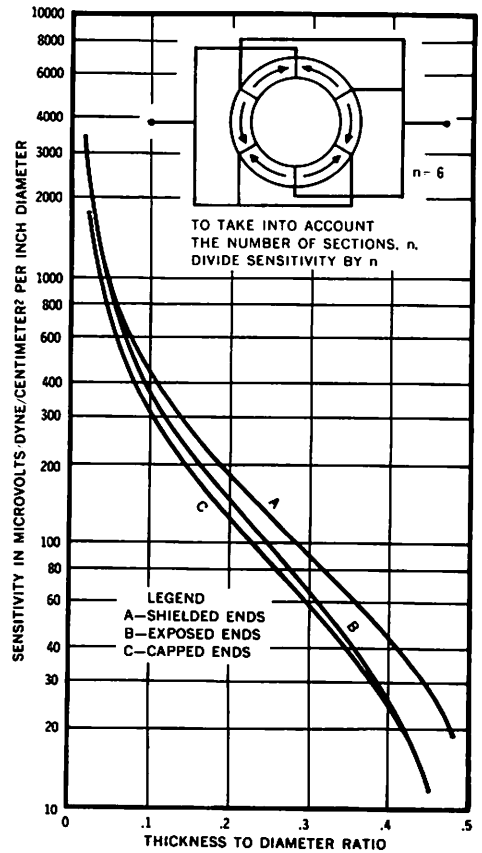
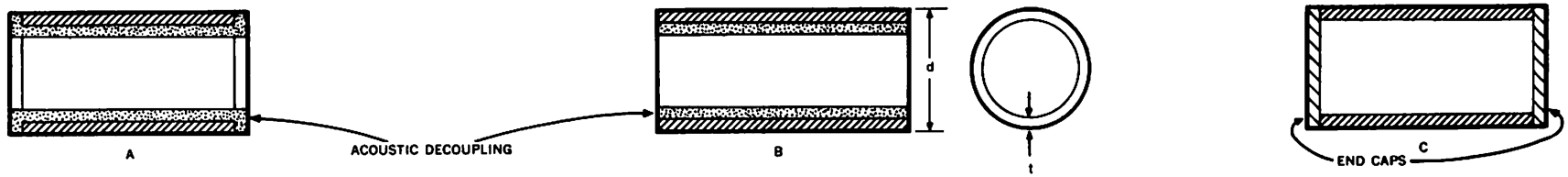
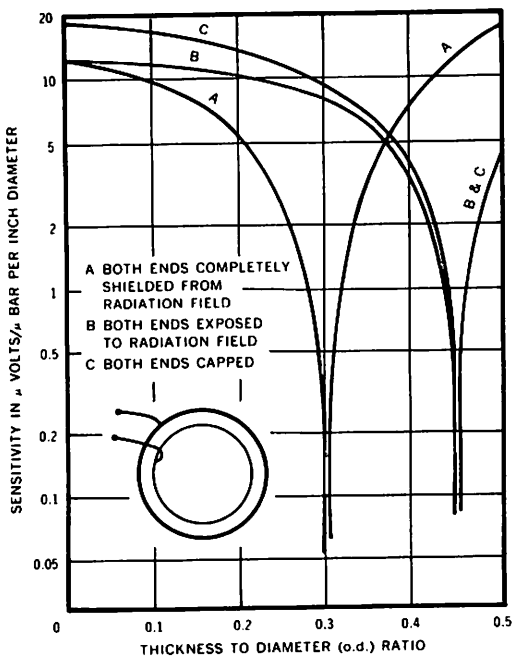
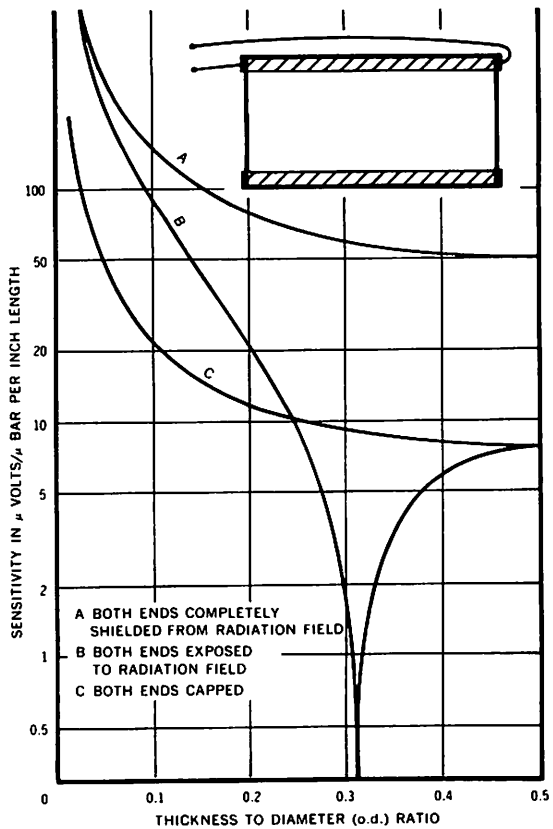




Fig. 38. Electroacoustic Sensitivity of Ceramic B Tubes.





SENSITIVITY IN μ VOLTS/μ BAR PER INCH DIAMETER
THICKNESS TO DIAMETER (o.d.) RATIO
A BOTH ENDS COMPLETELY SHIELDED FROM RADIATION FIELD
B BOTH ENDS EXPOSED TO RADIATION FIELD
C BOTH ENDS CAPPED
B & C


SENSITIVITY IN μ VOLTS/μ BAR PER INCH LENGTH
THICKNESS TO DIAMETER (o.d.) RATIO
A BOTH ENDS COMPLETELY SHIELDED FROM RADIATION FIELD
B BOTH ENDS EXPOSED TO RADIATION FIELD
C BOTH ENDS CAPPED

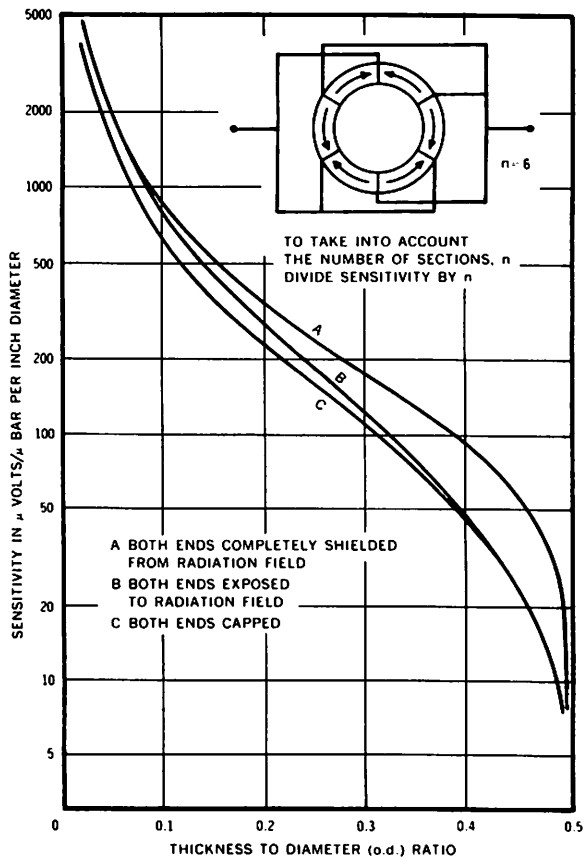
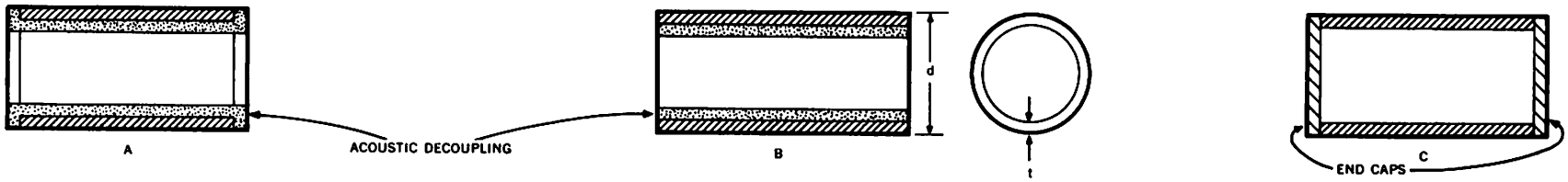
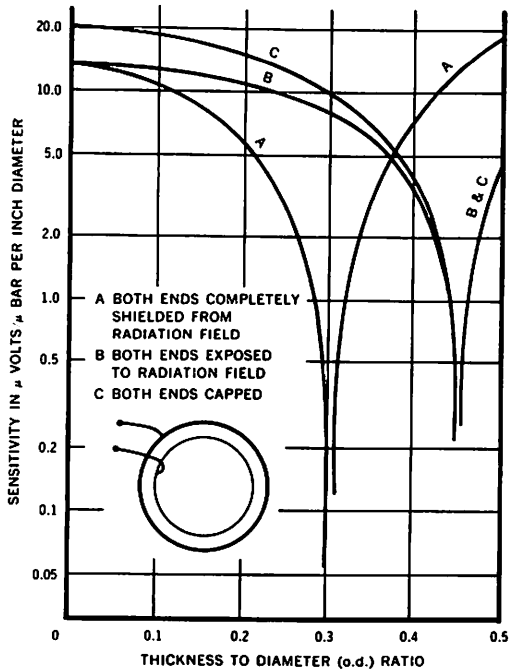
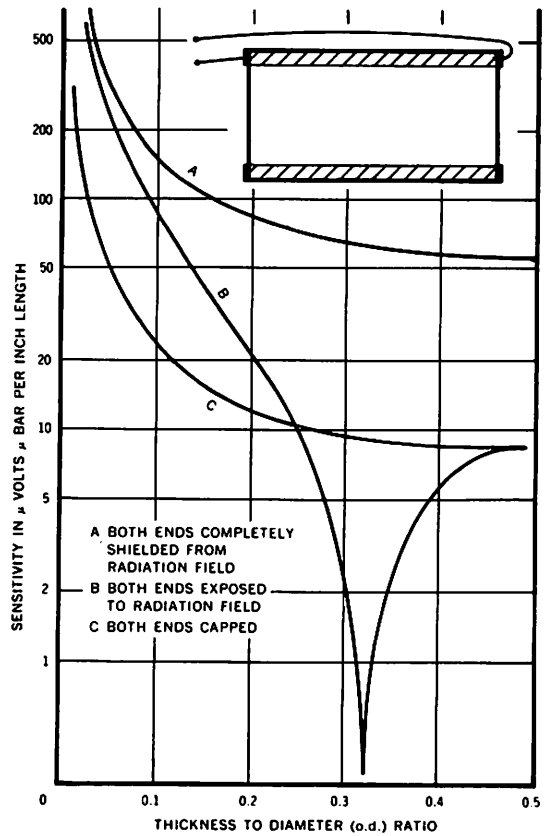

SENSITIVITY IN μ VOLTS/μ BAR PER INCH DIAMETER
THICKNESS TO DIAMETER (o.d.) RATIO
n = 6
TO TAKE INTO ACCOUNT THE NUMBER OF SECTIONS, n DIVIDE SENSITIVITY BY n
A BOTH ENDS COMPLETELY SHIELDED FROM RADIATION FIELD
B BOTH ENDS EXPOSED TO RADIATION FIELD
C BOTH ENDS CAPPED

Fig. 39. Electroacoustic Sensitivity of PZT4 Tubes.



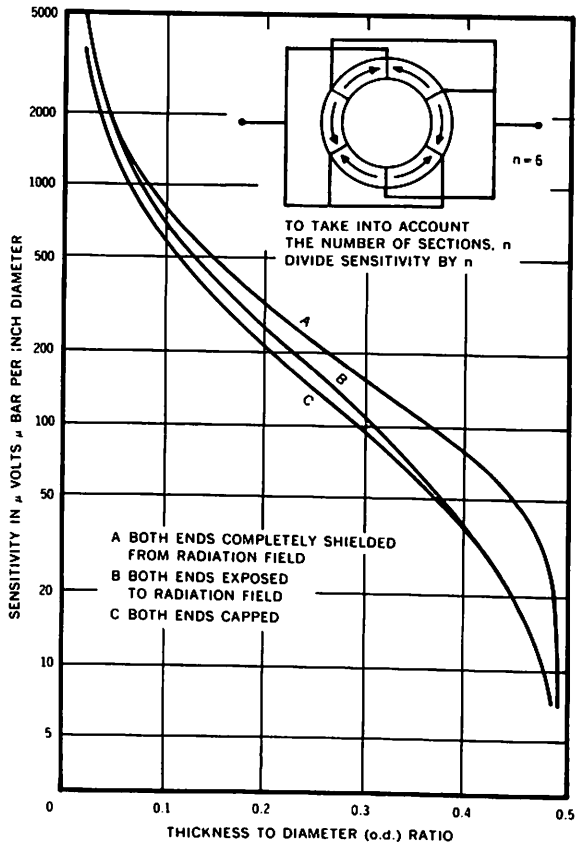




Fig. 40. Electroacoustic Sensitivity of PZT5A Tubes. For PZT5H Multiply Sensitivity by 0.8.

| | |
|---|---|
| TABLE I | Typical Symbols Employed in Describing Properties of Piezoelectric Materials |
| TABLE II | Units and Descriptions of Symbols |
| TABLE III | Piezoelectric Ceramics—Typical Room Temperature Data |
| TABLE IV | Temperature and Time Stability |
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| TABLE VI | Thermal Effects |
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# TABLE I

## Typical Symbols Employed in Describing Properties of Piezoelectric Materials

Strictly speaking, these symbols are used to identify properties of MATERIALS only, and should not be used to describe characteristics of actual physical elements made of these materials. However, for convenience, some liberties have been taken in the explanations—electric boundary conditions are identified by indicating locations and connections of electrodes.

---

**$S^D_{11}$**

- $D$ — Indicates that compliance is measured with electrode circuit open
- $11$ — Indicates that stress or strain is in 1 direction
- $11$ — Indicates that strain or stress is in 1 direction
- $S$ — Compliance $= \frac{\text{strain}}{\text{stress}}$

(All stresses, other than the stress involved in one subscript, are constant)

**$S^E_{36}$**

- $E$ — Indicates that compliance is measured with electrodes connected together
- $36$ — Indicates that stress or strain is in shear form around 3 axis
- $36$ — Indicates that strain or stress is in 3 direction
- $S$ — Compliance $= \frac{\text{strain}}{\text{stress}}$

(All stresses, other than the stress involved in one subscript, are constant)

---

**$K^T_1$**

- $T$ — Indicates that all stresses on material are constant—for example: zero external forces.
- $1$ — Indicates that electrodes are perpendicular to 1 axis
- $K$ — relative dielectric constant $= \frac{\epsilon^T_1}{\epsilon^o}$

**$K^S_3$**

- $S$ — Indicates that all strains in the material are constant—for example: material completely blocked preventing deformation in any direction
- $3$ — Indicates that electrodes are perpendicular to 3 axis
- $K$ — relative dielectric constant $= \frac{\epsilon^S_3}{\epsilon^o}$

---

**$k_{15}$**

- $15$ — Indicates that stress or strain is in shear form around 2 axis
- $15$ — Indicates that electrodes are perpendicular to 1 axis
- $k$ — Electromechanical coupling

**$k_p$**

- $p$ — This subscript used only for ceramics. Indicates electrodes perpendicular to 3 axis, and stress or strain equal in all directions perpendicular to 3 axis
- $k$ — Electromechanical coupling

---

**$d_{33}$**

- $33$ — Indicates that the piezoelectrically induced strain, or the applied stress, is in 3 direction
- $33$ — Indicates that electrodes are perpendicular to 3 axis
- $d$ — $\frac{\text{strain}}{\text{applied field}} = \frac{\text{short circuit charge/electrode area}}{\text{applied stress}}$

(All stresses, other than the stress involved in second subscript, are constant)

**$d_h$**

- $h$ — Indicates that stress is applied equally in 1, 2, and 3 directions (hydrostatic stress); and that electrodes are perpendicular to 3 axis for ceramics or 2 axis for Lithium sulfate.
- $d$ — $\frac{\text{short circuit charge/electrode area}}{\text{applied stress}}$

---

**$g_{31}$**

- $31$ — Indicates that applied stress, or piezoelectrically induced strain is in 1 direction
- $31$ — Indicates that electrodes are perpendicular to 3 axis
- $g$ — $\frac{\text{field}}{\text{applied stress}} = \frac{\text{strain}}{\text{applied charge/electrode area}}$

(All stresses, other than the stress involved in second subscript, are constant)

**$g_{15}$**

- $15$ — Indicates that applied stress, or piezoelectrically induced strain is in shear form around 2 axis
- $15$ — Indicates that electrodes are perpendicular to 1 axis
- $g$ — $\frac{\text{field}}{\text{applied stress}} = \frac{\text{strain}}{\text{applied charge/electrode area}}$

(All stresses, other than the stress involved in second subscript, are constant)

---

# TABLE II
## Units and Description of Symbols

$\epsilon_o$ = dielectric constant of free space = $8.85 \times 10^{-12}$ farads/meter.

$\epsilon^T/\epsilon_O$ = relative dielectric constant, free.

$\epsilon^S/\epsilon_O$ = relative dielectric constant, clamped.

$\tan \delta = \frac{1}{Q_E}$ = dissipation factor at 1 kcps, low electric field.

$k_p$ = planar coupling factor.

$k_{31}$ = transverse or lateral coupling factor.

$k_{33}$ = longitudinal coupling factor.

$k_{15}$ = shear coupling factor.

$k_t$ = thickness coupling factor (laterally clamped).

d = piezoelectric constant, strain/field at constant stress or charge density /stress at constant electric field, $10^{-12}$ meters/volt.

g = piezoelectric constant, electric field/stress at constant charge or strain/charge density at constant stress, $10^{-3}$ volt meters/newton.

$s^E$ = elastic compliance at constant electric field, $10^{-12}$ meter$^2$/newton.

$s^D$ = elastic compliance at constant charge density, $10^{-12}$ meter$^2$/newton.

$Q_M$ = mechanical Q. This is dependent upon configuration, and is given here for a thin disc.

$N_1$ = frequency constant of a thin bar, $f_R.\ell$, cycle meters/second.

$N_{3a}$ = frequency constant of a long slender bar electroded on ends, $f_a.\ell$, cycle meters/second.

$N_{3t}$ = frequency constant of a thin plate, $f_R.t$, cycle meters/seconds.

$v_3^D$ = velocity of a compressional wave parallel to polar axis $\{c_{33}^D = (v_3^D)^2 \rho\}$, meters/second.

$v_4^D$ = velocity of a shear wave perpendicular to polar axis with wave polarization parallel to polar axis $\{c_{44}^D = (v_4^D)^2 \rho\}$, meters/second.

$v_4^E$ = velocity of a shear wave parallel to polar axis, $\{c_{44}^E = (v_4^E)^2 \rho\}$, meters/ second.

$\rho$ = density, $10^3$ kg/m$^3$.

$\phi$ = temperature, °C.

P = polarization, $10^{-6}$ coulomb/cm$^2$ ($10^{-2}$ coulomb/m$^2$).

$\alpha$ = thermal expansion, $10^{-6}$/°C.

# TABLE III

## Piezoelectric Ceramics—Typical Room Temperature Data (Low Signal)

| | | Ceramic B | PZT-4 | PZT-5A | PZT-5H | Preliminary data PZT-8 |
|---|---|---|---|---|---|---|
| At one kcps* | $\epsilon_{33}^T/\epsilon_0$ | 1200 | 1300 | 1700 | 3400 | 1000 |
| | $\epsilon_{33}^S/\epsilon_0$ | 910 | 635 | 830 | 1470 | 600 |
| | $\epsilon_{11}^T/\epsilon_0$ | 1300 | 1475 | 1730 | 3130 | — |
| | $\epsilon_{11}^S/\epsilon_0$ | 1000 | 730 | 916 | 1700 | — |
| | $\tan \delta$ | 0.006 | 0.004 | 0.02 | 0.02 | 0.004 |
| | $k_p$ | −.33 | −.58 | −.60 | −.65 | −.50 |
| | $k_{31}$ | −.194 | −.334 | −.344 | −.388 | −.295 |
| | $k_{33}$ | .48 | .70 | .705 | .752 | .62 |
| | $k_{15}$ | .48 | .71 | .685 | .675 | — |
| | $k_t$ | .384 | .513 | .486 | .505 | — |
| | $k_{i3}$ | .491 | .715 | .715 | .754 | .63 |
| | $d_{31}$ | −58 | −123 | −171 | −274 | −93 |
| | $d_{33}$ | 149 | 289 | 374 | 593 | 218 |
| | $d_{15}$ | 242 | 496 | 584 | 741 | — |
| | $d_h$ | 33 | 43 | 32 | 45 | .32 |
| | $g_{31}$ | −5.5 | −11.1 | −11.4 | −9.11 | −10.5 |
| | $g_{33}$ | 14.1 | 26.1 | 24.8 | 19.7 | 24.5 |
| | $g_{15}$ | 21.0 | 39.4 | 38.2 | 26.8 | — |
| | $s_{11}^E$ | 8.6 | 12.3 | 16.4 | 16.5 | 11.1 |
| | $s_{33}^E$ | 9.1 | 15.5 | 18.8 | 20.7 | 13.9 |
| | $s_{44}^E$ | 22.2 | 39.0 | 47.5 | 43.5 | — |
| | $s_{12}^E$ | −2.6 | −4.05 | −5.74 | −4.78 | −3.7 |
| | $s_{13}^E$ | −2.7 | −5.31 | −7.22 | −8.45 | −4.8 |
| | $s_{11}^D$ | 8.3 | 10.9 | 14.4 | 14.05 | 10.1 |
| | $s_{33}^D$ | 7.0 | 7.90 | 9.46 | 8.99 | 8.5 |
| | $s_{44}^D$ | 17.1 | 19.3 | 25.2 | 23.7 | — |
| | $s_{12}^D$ | −2.9 | −5.42 | −7.71 | −7.27 | −4.5 |
| | $s_{13}^D$ | −1.9 | −2.10 | −2.98 | −3.05 | −2.5 |
| | $Q_M$ | 400 | 500 | 75 | 65 | 1000 |
| | $N_1$ | 2290 | 1650 | 1400 | 1420 | 1700 |
| | $N_{3t}$ | 2740 | 2000 | 1890 | 2000 | — |
| | $N_{3a}$ | 2530 | 2060 | 1845 | 1930 | 2000 |
| | $\rho$ | 5.55 | 7.5 | 7.75 | 7.5 | 7.6 |
| | Curie Point | 115°C | 328°C | 365°C | 193°C | 300°C |

*For PZT-5A the dielectric constants decrease about 2.4%/decade of frequency to at least 20 mcps and increase 2.4%/decade of frequency below 1 kcps to at least 1 cps.
For PZT-4 the dielectric constants decrease about 1.0%/decade of frequency to at least 1 mcps and increases 1.0%/decade of frequency below 1 kcps to at least 1 cps.

## TABLE IV

### Temperature and Time Stability

| | Ceramic B | PZT-4 | PZT-5A | PZT-5H | Preliminary data PZT-8 |
|---|---|---|---|---|---|
| Change in $k_p$/time decade | −1.8% | −2.3% | −0.2% | −0.35% | −2 |
| Change in $\epsilon_{33}^T$/time decade | −0.8% | −5.8% | −1% | −1.5% | −5 |
| Change in $N_1$/time decade | +0.5% | +1.5% | +0.2% | +0.25% | +1 |
| Volume resistivity in ohm meters | | | | | |
| 25°C | $>10^{10}$ | $>10^{10}$ | $>10^{11}$ | $>10^{11}$ | $>10^{10}$ |
| 100°C | $10^{7.5}$ | $10^{8.5}$ | $10^{11}$ | $10^{11}$ | $>10^{8.0}$ |
| 200°C | $10^{5}$ | $10^{6.5}$ | $10^{10}$ | $10^{10}$ | |
| Time constant, seconds | | | | | |
| 25°C | >100 | >100 | >2000 | >2000 | ~100 |
| 100°C | ~0.3 | ~5 | ~1800 | >2000 | ~2 |
| 200°C | ~0.002 | ~0.07 | ~250 | ~1000 | |

# TABLE V

## High Signal Properties

**(In this Table units of electric field are kv/cm or $10^5$ volts/m rms and stress in psi peak)**

| | Ceramic B | PZT-4 | PZT-5A | PZT-5H |
|---|---|---|---|---|
| AC depoling field | 3.5 | >10 | 7 | ~4 |
| AC field for tan $\delta$ = 0.04, 25°C[a] | 1.7 | 3.9 | 0.45 | 0.3 |
| % increase of $\epsilon_{33}^T$ at above electric field. | — | 17 | 11 | 5.3 |
| AC field for tan $\delta$ = 0.04, 100°C. | 1.0 at 75°C | 3.3 | 0.45 | 0.2 |
| Maximum rated static compressive stress (maintained) PARALLEL to polar axis. 25°C | 2,000 | 12,000 | 3,000 or 5,000[c] | 1,500 or 2,000[c] |
| Maximum rated static compressive stress (maintained) PARALLEL to polar axis. 100°C | 1,000 at 75°C | 6,000 | 3,000 | 1,000 or 1,500[c] |
| % change of $\epsilon_{33}^T$ with stress increase to rated maximum compressive stress at 25°C [b] | — | +25% approx. | −3% approx. [d] | −4% approx. [e] |
| % change of $d_{33}$ with stress increase to rated maximum compressive stress at 25°C. [b]. | — | ±15% approx. | −0% at 3,000<br>−13% at 5,000<br>approx. | −5% at 1,500<br>−7% at 2,000<br>approx. |
| Maximum rated compressive stress (cycled) PARALLEL to polar axis 25°C | 2,000 | 12,000 | 3,000 | 2,500 |
| Maximum rated compressive stress (cycled) PARALLEL to polar axis 100°C | 1,000 at 75°C | 6,000 | 3,000 | 2,000 |
| Maximum rated static compressive stress (Maintained) PERPENDICULAR to polar axis 25°C | 2,000 | 8,000 | 2,000 | 1,500 |
| Maximum rated static compressive stress (Maintained) PERPENDICULAR to polar axis 100°C | 1,000 at 75°C | 4,000 | 2,000 | 1,000 |
| % change of $\epsilon_{33}^T$ with stress increase to rated maximum compressive stress at 25°C. [b] | — | +10% approx. | — | — |
| % change of $d_{31}$ with stress increase to rated maximum compressive stress at 25°C. [b] | — | −10%[f] approx. | — | — |
| Maximum rated hydrostatic pressure | 20,000 | 50,000 | 20,000 | 20,000 |
| Compressive strength | >50,000 | >75,000 | >75,000 | >75,000 |
| Tensile strength, static | 7,500 | 11,000 | 11,000 | 11,000 |
| tensile strength, dynamic (peak) [g] | 3,000 | 3,500 | 4,000 | 4,000 |
| Mechanical Q at ~0 psi (peak dynamic stress) | 400 | 500 | 75 | 65 |
| Mechanical Q at 1,000 psi (peak dynamic stress) | 140 approx. | 180 approx. | 25 approx. | — |
| Mechanical Q at 2,000 psi (peak dynamic stress) | 85 approx. | 110 approx. | 25 approx. | — |
| % increase in $s_{11}^E$ at 1,000 psi (peak dynamic stress) | 1.7 approx. | 1.7 approx. | 10.5 approx. | — |
| % increase in $s_{11}^E$ at 2,000 psi (peak dynamic stress) | 3.7 approx. | 3.7 approx. | 17 approx. | — |
| Polarization 25°C | 8$\mu$ coul/cm$^2$ | 30 | 38 | 33 |
| Coercive Field 25°C | ~5 | h) | 12 | 6.5 |

a) The value of tan $\delta$ at a given electric field is a function of time after poling or after any major disturbance such as exposure to an elevated temperature.

b) After appropriate stabilizing treatment. This consists of the temperature stabilization discussed previously plus a few minutes soak at the appropriate static stress. The temperature stabilization is, however, more important than the stress soak.

c) The higher figure applies to a receiver, the lower to a radiator. The recommended use of PZT-5A or PZT-5H is the former.

d) In range to 10,000 psi.

e) In range to 5,000 psi.

f) The lateral d-constant perpendicular to the stress and polar axis is up about 20%.

g) These figures are dependent upon configuration and perfection of fabrication. The static tensile strength figures were obtained from bending tests on thin "Bimorph" structures, while the dynamic tensile strength figures were obtained from measurements of high amplitude resonant vibration of rings. The latter tests are more sensitive to minor flaws.

h) Coercive field values for PZT-4 are not well defined, as values from hysteresis loops are time dependent and dependent on amplitude of peak electric field.

i) Coercive field is quasi static value; it is not rms.

# TABLE VI
## Thermal Effects

**A.** Pyroelectric effects, $(\partial P/\partial\theta)_T$ in $10^{-6}$ coul/cm² °C ($10^{-2}$ coul/m²°C)

| Temperature, °C | Ceramic B[b] | PZT-4 | PZT-5A | |
|---|---|---|---|---|
| | First Heating | First Heating | First Heating | Subsequent Heatings |
| −196 | — | — | −0.02 | −0.02 |
| − 80 | −0.025 | −0.025 | −0.03 | −0.02 |
| − 60 | −0.025 | −0.025 | −0.03 | −0.02 |
| 0 | −0.022 | −0.025 | −0.04 | −0.02 |
| 30 | −0.022 | −0.028 | −0.06 | −0.02 |
| 60 | −0.022 | −0.026 | −0.07 | −0.02 |
| 80 | (a) | −0.025 | −0.09 | −0.02 |
| 100 | (a) | (a) | −0.11 | −0.02 |
| 200 | 0 | (a) | −0.17 | −0.04 |
| 300 | 0 | (a) | −0.23 | −0.09 |

a) Above about 80°C the pyroelectric effect is masked by anomalous dielectric charges.
b) Ceramic B has a very sharp peak in the pyroelectric constant at the orthorhombic-tetragonal phase transition near −30°C. The peak value is about 0.3 μcoul/cm²°C.

**B.** Thermal Expansion Coefficient ($\alpha$ in $10^{-6}$/°C)

| | Poled PZT-5A | | | | Poled PZT-4 | | | |
|---|---|---|---|---|---|---|---|---|
| | First Heating | | Subsequent Heatings | | First Heating | | Subsequent Heatings | |
| °C | $\alpha_1$ | $\alpha_3$ | $\alpha_1$ | $\alpha_3$ | $\alpha_1$ | $\alpha_3$ | $\alpha_1$ | $\alpha_3$ |
| 0 | +1.5 | +2 | +1 | +4 | +1.5 | +0.1 | +3.8 | +1.7 |
| 50 | +1.5 | +2 | +1.4 | +4 | +4.5 | −0.1 | +3.8 | +1.7 |
| 100 | +6 | −6 | +2 | +3 | +5.8 | −6 | +3.8 | −1 |
| 150 | +6 | −7 | +2.7 | +1 | +6.4 | −6 | +3.8 | −1.4 |
| 200 | +5 | −7 | +3.3 | −1.6 | +5.4 | −6.1 | +3.4 | −2.4 |
| 250 | +4.2 | −6 | +3.9 | −4.2 | | | | |

| | Virgin (Unpoled) | |
|---|---|---|
| | PZT-5A | PZT-4 |
| | $\alpha$ | $\alpha$ |
| 0 | +2.5 | +2.0 |
| 50 | +2.1 | +1.8 |
| 100 | +2.0 | +1.5 |
| 150 | +1.8 | +1.1 |
| 200 | +1.5 | +1.0 |
| 250 | +1.0 | +0.3 |
| 300 | +0.7 | 0.0 |
| 350 | −3.0 | +6.2 |
| 400 | +5 | +7.8 |
| 500 | +8.2 | +8.2 |

| | Ceramic B | |
|---|---|---|
| | First Heating | |
| °C | $\alpha_1$ | $\alpha_3$ |
| 30 | +7.5 | +4.7 |
| 40 | +7.5 | +4.7 |
| 50 | +7.5 | +4.7 |
| 60 | +7.5 | +4.7 |
| 70 | +7.5 | +4.3 |
| 80 | +7.5 | +3.2 |
| 90 | +7.5 | +1.8 |
| 100 | +7.5 | 0 |
| | Above 120°C | |
| | $\alpha$ = +9 | |

As noted above, thermal expansion of PZT-4 and PZT-5A is extremely anisotropic only on first heating, and on first heating only above about 50°C. With Ceramic B thermal expansion is markedly anisotropic only above about 80°C even on first heating.

**C.** Heat Capacity.

PZT, ~420 joules/kg°C (138 joules/°C mole).
Ceramic B, ~500 joules/kg°C (117 joules/°C mole).

**D.** Thermal Conductivity.

PZT, ~1.8 watts/meter°C.
Ceramic B, ~2.5 watts/meter°C.

# TABLE VII

## Piezoelectric Crystals—Room Temperature Data

| | |
|---|---|
| **ROCHELLE SALT** | |
| $\epsilon_{11}^{T}/\epsilon_{O}$ (Low field, @ 30°C. See fig. 32) | 350 |
| $\epsilon_{11}^{S}/\epsilon_{O}$ (Low field, @ 30°C. See fig. 32) | 154 |
| $g_{14}$ | 180 x ($10^{-3}$) |
| $S_{44}^{D}$ | 77 x ($10^{-12}$) |
| $k_{14}$ (at 30°C) | .75 |
| $\rho$ | 1.77 |
| Volume resistivity | $>10^{10}$ |
| $\alpha_1$ | 28 x $10^{-6}$/°C |
| $\alpha_2$ | 17 x $10^{-6}$/°C |
| $\alpha_3$ | 20 x $10^{-6}$/°C |
| Max. safe operating temperature | 45°C |
| Min. safe relative humidity (unprotected crystal) | 40% |
| Max. safe relative humidity (unprotected crystal) | 70% |
| **AMMONIUM DIHYDROGEN PHOSPHATE (ADP)** | |
| $\epsilon_{33}^{T}/\epsilon_{O}$ | 15.3 |
| $\epsilon_{33}^{S}/\epsilon_{O}$ | 13.8 |
| $k_{36}$ | .32 |
| $d_{36}$ | 48 x ($10^{-12}$) |
| $g_{36}$ | 354 x ($10^{-3}$) |
| $S_{66}^{E}$ | 166 x ($10^{-12}$) |
| $S_{66}^{D}$ | 149 x ($10^{-12}$) |
| $\rho$ | 1.8 |
| Volume resistivity | See fig. 33 |
| $\alpha 1$ | 35 x $10^{-6}$/°C |
| $\alpha 2$ | 35 x $10^{-6}$/°C |
| $\alpha 3$ | 1.7 x $10^{-6}$/°C |
| Max. safe operating temperature | 125°C |
| Min. safe relative humidity | 0% |
| Max. safe relative humidity (unprotected crystal) | 94% |
| **LITHIUM SULPHATE** | |
| $\epsilon_{22}^{T}/\epsilon_{O}$ | 10.3 |
| $k_T$ | .38 |
| $d_{22}$ | 16 x ($10^{-12}$) |
| $d_h$ | 13.5 x ($10^{-12}$) |
| $g_{22}$ | 175 x ($10^{-3}$) |
| $S_{22}^{E}$ | 22.5 x ($10^{-12}$) |
| $\rho$ | 2.055 |
| Volume resistivity | $>10^{10}$ |
| $\alpha 1$ | −5 x $10^{-6}$/°C |
| $\alpha 2$ | 28 x $10^{-6}$/°C |
| $\alpha 3$ | 16 x $10^{-6}$/°C |
| Max. safe operating temperature | 75°C |
| Min. safe relative humidity | 0% |
| Max. safe relative humidity (unprotected crystal) | 95% |

## CONVERSION CHARTS

The conversion charts presented in this report were prepared to minimize confusion between the various units most frequently encountered in measuring piezoelectric shapes. Included are charts for angular, linear, area and volume measure: force, torque, pressure, and density; and compliance and mechanical impedance. In addition there are charts for the inverse of several of these measures.

The charts of inverse measure are used for all conversions of the type X per unit A to X per unit B. An example of this case is volts per inch to be converted to volts per meter. It is sometimes possible to use the charts for multiple conversions when the specific units are not available on any of the charts. Thus, degrees per ounce-inch torsional compliance can be expressed as radians per newton-meter by first converting to radians per ounce-inch and then to radians per newton-meter. The desired overall conversion factor is the product of the two factors, $1.745 \times 10^{-2}$ (degrees to radians) times $1.416 \times 10^{2}$ (X per ounce-inch to X per newton-meter) giving number of degrees per ounce-inch times 2.471 equals number of radians per newton-meter.

Below are the fundamental constants used in the preparation of the charts.

1 meter = 39.37 inches.
1 pound = .453592 kilograms.
Acceleration due to gravity = 980.665 $cm/sec^2$.
Density of $H_2O$ at 4°C = .999973 $grams/cm^3$.
Density of $H_g$ at 0°C = 13.5951 $grams/cm^3$.
Density of sea water at 0°C = 1.028 $grams/cm^3$.

## LENGTH

| Multiply Number of → BY / To Obtain ↓ | Millimeters | Centimeters | Meters | Mils | Inches | Feet |
|---|---|---|---|---|---|---|
| Millimeters | 1 | 10 | $10^{3}$ | $2.540 \cdot 10^{-2}$ | $2.540 \cdot 10$ | $3.048 \cdot 10^{2}$ |
| Centimeters | $10^{-1}$ | 1 | $10^{2}$ | $2.540 \cdot 10^{-3}$ | 2.540 | $2.048 \cdot 10$ |
| Meters | $10^{-3}$ | $10^{-2}$ | 1 | $2.540 \cdot 10^{-5}$ | $2.540 \cdot 10^{-2}$ | $3.048 \cdot 10^{-1}$ |
| Mils | $3.937 \cdot 10$ | $3.937 \cdot 10^{2}$ | $3.937 \cdot 10^{4}$ | 1 | $10^{3}$ | $1.200 \cdot 10^{4}$ |
| Inches | $3.937 \cdot 10^{-2}$ | $3.937 \cdot 10^{-1}$ | $3.937 \cdot 10$ | $10^{-3}$ | 1 | $1.200 \cdot 10$ |
| Feet | $3.281 \cdot 10^{-3}$ | $3.281 \cdot 10^{-2}$ | 3.281 | $8.333 \cdot 10^{-5}$ | $8.333 \cdot 10^{-2}$ | 1 |

## INVERSE LENGTH

| Multiply Number of → BY / To Obtain ↓ | X Per Millimeter | X Per Centimeter | X Per Meter | X Per Mil | X Per Inch | X Per Foot |
|---|---|---|---|---|---|---|
| X Per Millimeter | 1 | $10^{-1}$ | $10^{-3}$ | $3.937 \cdot 10$ | $3.937 \cdot 10^{-2}$ | $3.281 \cdot 10^{-3}$ |
| X Per Centimeter | 10 | 1 | $10^{-2}$ | $3.937 \cdot 10^{2}$ | $3.937 \cdot 10^{-1}$ | $3.281 \cdot 10^{-2}$ |
| X Per Meter | $10^{3}$ | $10^{2}$ | 1 | $3.937 \cdot 10^{4}$ | $3.937 \cdot 10$ | 3.281 |
| X Per Mil | $2.540 \cdot 10^{-2}$ | $2.540 \cdot 10^{-3}$ | $2.540 \cdot 10^{-5}$ | 1 | $10^{-3}$ | $8.333 \cdot 10^{-5}$ |
| X Per Inch | $2.540 \cdot 10$ | 2.540 | $2.540 \cdot 10^{-2}$ | $10^{3}$ | 1 | $8.3331 \cdot 0^{-2}$ |
| X Per Foot | $3.048 \cdot 10^{2}$ | $3.048 \cdot 10$ | $3.048 \cdot 10^{-1}$ | $1.200 \cdot 10^{4}$ | $1.200 \cdot 10$ | 1 |

## AREA

| Multiply Number of → BY ↘ To Obtain ↓ | Square Millimeters | Square Centimeters | Square Meters | Circular Mils | Square Inches | Square Feet |
|---|---|---|---|---|---|---|
| Square Millimeters | 1 | $10^{2}$ | $10^{6}$ | $5.067 \cdot 10^{-4}$ | $6.452 \cdot 20^{2}$ | $9.290 \cdot 10^{4}$ |
| Square Centimeters | $10^{-2}$ | 1 | $10^{4}$ | $5.067 \cdot 10^{-6}$ | 6.452 | $9.290 \cdot 10^{2}$ |
| Square Meters | $10^{-6}$ | $10^{-4}$ | 1 | $5.067 \cdot 10^{-10}$ | $6.452 \cdot 10^{-4}$ | $9.290 \cdot 10^{-2}$ |
| Circular Mils | $1.973 \cdot 10^{3}$ | $1.973 \cdot 10^{5}$ | $1.973 \cdot 10^{9}$ | 1 | $1.273 \cdot 10^{6}$ | $1.833 \cdot 10^{8}$ |
| Square Inches | $1.550 \cdot 10^{-3}$ | $1.550 \cdot 10^{-1}$ | $1.550 \cdot 10^{3}$ | $7.854 \cdot 10^{-7}$ | 1 | $1.440 \cdot 10^{2}$ |
| Square Feet | $1.076 \cdot 10^{-5}$ | $1.076 \cdot 10^{-3}$ | $1.076 \cdot 10$ | $5.454 \cdot 10^{-9}$ | $6.944 \cdot 10^{-3}$ | 1 |

## INVERSE AREA

| Multiply Number of → BY ↘ To Obtain ↓ | X Per Square Millimeter | X Per Square Centimeter | X Per Square Meter | X Per Circular Mil | X Per Square Inch | X Per Square Foot |
|---|---|---|---|---|---|---|
| X Per Square Millimeter | 1 | $10^{-2}$ | $10^{-6}$ | $1.973 \cdot 10^{3}$ | $1.550 \cdot 10^{-3}$ | $1.076 \cdot 10^{-5}$ |
| X Per Square Centimeter | $10^{2}$ | 1 | $10^{-4}$ | $1.973 \cdot 10^{5}$ | $1.550 \cdot 10^{-1}$ | $1.076 \cdot 10^{-3}$ |
| X Per Square Meter | $10^{6}$ | $10^{4}$ | 1 | $1.973 \cdot 10^{9}$ | $1.550 \cdot 10^{3}$ | $1.076 \cdot 10$ |
| X Per Circular Mil | $5.067 \cdot 10^{-4}$ | $5.067 \cdot 10^{-6}$ | $5.067 \cdot 10^{-10}$ | 1 | $7.854 \cdot 10^{-7}$ | $5.454 \cdot 10^{-9}$ |
| X Per Square Inch | $6.452 \cdot 10^{2}$ | 6.452 | $6.452 \cdot 10^{-4}$ | $1.273 \cdot 10^{6}$ | 1 | $6.944 \cdot 10^{-3}$ |
| X Per Square Foot | $9.290 \cdot 10^{4}$ | $9.290 \cdot 10^{2}$ | $9.290 \cdot 10^{-2}$ | $1.833 \cdot 10^{8}$ | $1.440 \cdot 10^{2}$ | 1 |

## ANGULAR MEASURE

| Multiply Number of → / BY / To Obtain ↓ | Seconds | Minutes | Degrees | Radians |
|---|---|---|---|---|
| Seconds | 1 | 6.000·10 | $3.600 \cdot 10^{3}$ | $2.063 \cdot 10^{5}$ |
| Minutes | $1.667 \cdot 10^{-2}$ | 1 | 6.000·10 | $3.438 \cdot 10^{3}$ |
| Degrees | $2.778 \cdot 10^{-4}$ | $1.667 \cdot 10^{-2}$ | 1 | 5.730·10 |
| Radians | $4.848 \cdot 10^{-6}$ | $2.909 \cdot 10^{-4}$ | $1.745 \cdot 10^{-2}$ | 1 |

## INVERSE ANGULAR MEASURE

| Multiply Number of → / BY / To Obtain ↓ | X Per Second | X Per Minute | X Per Degree | X Per Radian |
|---|---|---|---|---|
| X Per Second | 1 | $1.667 \cdot 10^{-2}$ | $2.778 \cdot 10^{-4}$ | $4.848 \cdot 10^{-6}$ |
| X Per Minute | 6.000·10 | 1 | $1.667 \cdot 10^{-2}$ | $2.909 \cdot 10^{-4}$ |
| X Per Degree | $3.600 \cdot 10^{3}$ | 6.000·10 | 1 | $1.745 \cdot 10^{-2}$ |
| X Per Radian | $2.063 \cdot 10^{5}$ | $3.438 \cdot 10^{3}$ | 5.730·10 | 1 |

## VOLUME

| Multiply Number of → / BY / To Obtain ↓ | Cubic Centimeters | Cubic Meters | Cubic Inches | Cubic Feet |
|---|---|---|---|---|
| Cubic Centimeters | 1 | $10^{6}$ | 1.639·10 | $2.832 \cdot 10^{4}$ |
| Cubic Meters | $10^{-6}$ | 1 | $1.639 \cdot 10^{-5}$ | $2.832 \cdot 10^{-2}$ |
| Cubic Inches | $6.102 \cdot 10^{-2}$ | $6.102 \cdot 10^{4}$ | 1 | $1.728 \cdot 10^{3}$ |
| Cubic Feet | $3.531 \cdot 10^{-5}$ | 3.531·10 | $5.787 \cdot 10^{-4}$ | 1 |

## INVERSE VOLUME

| Multiply Number of → / BY / To Obtain ↓ | X Per Cubic Centimeter | X Per Cubic Meter | X Per Cubic Inch | X Per Cubic Foot |
|---|---|---|---|---|
| X Per Cubic Centimeter | 1 | $10^{-6}$ | $6.102 \cdot 10^{-2}$ | $3.315 \cdot 10^{-5}$ |
| X Per Cubic Meter | $10^{6}$ | 1 | $6.102 \cdot 10^{4}$ | 3.531·10 |
| X Per Cubic Inch | 1.639·10 | $1.639 \cdot 10^{-5}$ | 1 | $5.787 \cdot 10^{-4}$ |
| X Per Cubic Foot | $2.832 \cdot 10^{4}$ | $2.832 \cdot 10^{-2}$ | $1.728 \cdot 10^{3}$ | 1 |

## FORCE

| Multiply Number of → / BY / To Obtain ↓ | Dynes | Newtons | Grams | Kilograms | Ounces | Pounds |
|---|---|---|---|---|---|---|
| **Dynes** | 1 | $10^{5}$ | $9.807 \cdot 10^{2}$ | $9.807 \cdot 10^{5}$ | $2.780 \cdot 10^{4}$ | $4.448 \cdot 10^{5}$ |
| **Newtons** | $10^{-5}$ | 1 | $9.807 \cdot 10^{-3}$ | 9.807 | $2.780 \cdot 10^{-1}$ | 4.448 |
| **Grams** | $1.020 \cdot 10^{-3}$ | $1.020 \cdot 10^{2}$ | 1 | $10^{3}$ | $2.835 \cdot 10$ | $4.536 \cdot 10^{2}$ |
| **Kilograms** | $1.020 \cdot 10^{-6}$ | $1.020 \cdot 10^{-1}$ | $10^{-3}$ | 1 | $2.835 \cdot 10^{-2}$ | $4.536 \cdot 10^{-1}$ |
| **Ounces** | $3.597 \cdot 10^{-5}$ | 3.597 | $3.527 \cdot 10^{-2}$ | $3.527 \cdot 10$ | 1 | $1.600 \cdot 10$ |
| **Pounds** | $2.248 \cdot 10^{-6}$ | $2.248 \cdot 10^{-1}$ | $2.205 \cdot 10^{-3}$ | 2.205 | $6.250 \cdot 10^{-2}$ | 1 |

## INVERSE FORCE

| Multiply Number of → / BY / To Obtain ↓ | X Per Dyne | X Per Newton | X Per Gram | X Per Kilogram | X Per Ounce | X Per Pound |
|---|---|---|---|---|---|---|
| **X Per Dyne** | 1 | $10^{-5}$ | $1.020 \cdot 10^{-3}$ | $1.020 \cdot 10^{-6}$ | $3.597 \cdot 10^{-5}$ | $2.248 \cdot 10^{-6}$ |
| **X Per Newton** | $10^{5}$ | 1 | $1.020 \cdot 10^{2}$ | $1.020 \cdot 10^{-1}$ | 3.597 | $2.248 \cdot 10^{-1}$ |
| **X Per Gram** | $9.807 \cdot 10^{2}$ | $9.807 \cdot 10^{-3}$ | 1 | $10^{-3}$ | $3.527 \cdot 10^{-2}$ | $2.205 \cdot 10^{-3}$ |
| **X Per Kilogram** | $9.807 \cdot 10^{5}$ | 9.807 | $10^{3}$ | 1 | $3.527 \cdot 10$ | 2.205 |
| **X Per Ounce** | $2.780 \cdot 10^{4}$ | $2.780 \cdot 10^{-1}$ | $2.835 \cdot 10$ | $2.835 \cdot 10^{-2}$ | 1 | $6.250 \cdot 10^{-2}$ |
| **X Per Pound** | $4.448 \cdot 10^{5}$ | 4.448 | $4.536 \cdot 10^{2}$ | $4.536 \cdot 10^{-1}$ | $1.600 \cdot 10$ | 1 |

## TORQUE

| Multiply Number of → BY ↘ To Obtain ↓ | Dyne Centimeter | Newton Meter | Gram Centimeters | Kilogram Meters | Ounce Inches | Pound Feet |
|---|---|---|---|---|---|---|
| Dyne Centimeters | 1 | $10^{7}$ | $9.807 \cdot 10^{2}$ | $9.807 \cdot 10^{7}$ | $7.062 \cdot 10^{4}$ | $1.356 \cdot 10^{7}$ |
| Newton Meters | $10^{-7}$ | 1 | $9.807 \cdot 10^{-5}$ | 9.807 | $7.062 \cdot 10^{-3}$ | 1.356 |
| Gram Centimeters | $1.020 \cdot 10^{-3}$ | $1.020 \cdot 10^{4}$ | 1 | $10^{5}$ | $7.201 \cdot 10$ | $1.383 \cdot 10^{4}$ |
| Kilogram Meters | $1.020 \cdot 10^{-8}$ | $1.020 \cdot 10^{-1}$ | $10^{-5}$ | 1 | $7.201 \cdot 10^{-4}$ | $1.383 \cdot 10^{-1}$ |
| Ounce Inches | $1.416 \cdot 10^{-5}$ | $1.416 \cdot 10^{2}$ | $1.389 \cdot 10^{-2}$ | $1.389 \cdot 10^{3}$ | 1 | $1.920 \cdot 10^{2}$ |
| Pound Feet | $7.376 \cdot 10^{-8}$ | $7.376 \cdot 10^{-1}$ | $7.233 \cdot 10^{-5}$ | 7.233 | $5.208 \cdot 10^{-3}$ | 1 |

## INVERSE TORQUE

| Multiply Number of → BY ↘ To Obtain ↓ | X Per Dyne Centimeter | X Per Newton Meter | X Per Gram Centimeter | X Per Kilogram Meter | X Per Ounce Inch | X Per Pound Foot |
|---|---|---|---|---|---|---|
| X Per Dyne Centimeter | 1 | $10^{-7}$ | $1.020 \cdot 10^{-3}$ | $1.020 \cdot 10^{-8}$ | $1.416 \cdot 10^{-5}$ | $7.376 \cdot 10^{-8}$ |
| X Per Newton Meter | $10^{7}$ | 1 | $1.020 \cdot 10^{4}$ | $1.020 \cdot 10^{-1}$ | $1.416 \cdot 10^{2}$ | $7.376 \cdot 10^{-1}$ |
| X Per Gram Centimeter | $9.807 \cdot 10^{2}$ | $9.807 \cdot 10^{-5}$ | 1 | $10^{5}$ | $1.389 \cdot 10^{-2}$ | $7.233 \cdot 10^{-5}$ |
| X Per Kilogram Meter | $9.807 \cdot 10^{7}$ | 9.807 | $10^{5}$ | 1 | $1.389 \cdot 10^{3}$ | 7.233 |
| X Per Ounce Inch | $7.062 \cdot 10^{4}$ | $7.062 \cdot 10^{-3}$ | $7.201 \cdot 10$ | $7.201 \cdot 10^{-4}$ | 1 | $5.208 \cdot 10^{-3}$ |
| X Per Pound Foot | $1.356 \cdot 10^{7}$ | 1.356 | $1.383 \cdot 10^{4}$ | $1.383 \cdot 10^{-1}$ | $1.920 \cdot 10^{2}$ | 1 |

## PRESSURE

| Multiply Number of → BY ↘ / To Obtain ↓ | Dynes Per Square Centimeter | Newtons Per Square Meter | Kilograms Per Square Meter | Pounds Per Square Inch | Centimeters of Mercury at 0°C | Feet of Fresh Water at 4°C | Feet of Sea Water* at 0°C |
|---|---|---|---|---|---|---|---|
| Dynes Per Square Centimeter | 1 | 10 | $9.807 \cdot 10$ | $6.895 \cdot 10^{4}$ | $1.333 \cdot 10^{4}$ | $2.989 \cdot 10^{4}$ | $3.073 \cdot 10^{4}$ |
| Newtons Per Square Meter | $10^{-1}$ | 1 | 9.807 | $6.895 \cdot 10^{3}$ | $1.333 \cdot 10^{3}$ | $2.989 \cdot 10^{3}$ | $3.073 \cdot 10^{3}$ |
| Kilograms Per Square Meter | $1.020 \cdot 10^{-2}$ | $1.020 \cdot 10^{-1}$ | 1 | $7.031 \cdot 10^{2}$ | $1.360 \cdot 10^{2}$ | $3.048 \cdot 10^{2}$ | $3.133 \cdot 10^{2}$ |
| Pounds Per Square Inch | $1.450 \cdot 10^{-5}$ | $1.450 \cdot 10^{-4}$ | $1.422 \cdot 10^{-3}$ | 1 | $1.934 \cdot 10^{-1}$ | $4.335 \cdot 10^{-1}$ | $4.457 \cdot 10^{-1}$ |
| Centimeters of Mercury at 0°C | $7.501 \cdot 10^{-5}$ | $7.501 \cdot 10^{-4}$ | $7.356 \cdot 10^{-3}$ | 5.171 | 1 | 2.242 | 2.305 |
| Feet of Fresh Water at 4°C | $3.346 \cdot 10^{-5}$ | $3.346 \cdot 10^{-4}$ | $3.281 \cdot 10^{-3}$ | 2.307 | $4.460 \cdot 10^{-1}$ | 1 | 1.028 |
| Feet of Sea Water* at 0°C | $3.254 \cdot 10^{-5}$ | $3.254 \cdot 10^{-4}$ | $3.191 \cdot 10^{-3}$ | 2.244 | $4.339 \cdot 10^{-1}$ | $9.727 \cdot 10^{-1}$ | 1 |

## INVERSE PRESSURE

| Multiply Number of → BY ↘ / To Obtain ↓ | X Per Dyne Per Square Centimeter | X Per Newton Per Square Meter | X Per Kilogram Per Square Meter | X Per Pound Per Square Inch | X Per Centimeter of Mercury at 0°C | X Per Foot of Fresh Water at 4°C | X Per Foot of Sea Water* at 0°C |
|---|---|---|---|---|---|---|---|
| X Per Dyne Per Square Centimeter | 1 | $10^{-1}$ | $1.020 \cdot 10^{-2}$ | $1.450 \cdot 10^{-5}$ | $7.501 \cdot 10^{-5}$ | $3.346 \cdot 10^{-5}$ | $3.254 \cdot 10^{-5}$ |
| X Per Newton Per Square Meter | 10 | 1 | $1.020 \cdot 10^{-1}$ | $1.450 \cdot 10^{-4}$ | $7.501 \cdot 10^{-4}$ | $3.346 \cdot 10^{-4}$ | $3.254 \cdot 10^{-4}$ |
| X Per Kilogram Per Square Meter | $9.807 \cdot 10$ | 9.807 | 1 | $1.422 \cdot 10^{-3}$ | $7.356 \cdot 10^{-3}$ | $3.281 \cdot 10^{-3}$ | $3.191 \cdot 10^{-3}$ |
| X Per Pound Per Square Inch | $6.895 \cdot 10^{4}$ | $6.895 \cdot 10^{3}$ | $7.031 \cdot 10^{2}$ | 1 | 5.171 | 2.307 | 2.244 |
| X Per Centimeter of Mercury at 0°C. | $1.333 \cdot 10^{4}$ | $1.333 \cdot 10^{3}$ | $1.360 \cdot 10^{2}$ | $1.934 \cdot 10^{-1}$ | 1 | $4.460 \cdot 10^{-1}$ | $4.339 \cdot 10^{-1}$ |
| X Per Foot of Fresh Water at 4°C. | $2.989 \cdot 10^{4}$ | $2.989 \cdot 10^{3}$ | $3.048 \cdot 10^{2}$ | $4.335 \cdot 10^{-1}$ | 2.242 | 1 | $9.727 \cdot 10^{-1}$ |
| X Per Foot of Sea Water* at 0°C. | $3.073 \cdot 10^{4}$ | $3.073 \cdot 10^{3}$ | $3.133 \cdot 10^{2}$ | $4.457 \cdot 10^{-1}$ | 2.305 | 1.028 | 1 |

## DENSITY

| Multiply Number of → BY ↘ To Obtain ↓ | Grams Per Cubic Centimeter | Kilograms Per Cubic Meter | Grams Per Cubic Inch | Ounces Per Cubic Inch | Pounds Per Cubic Inch | Pounds Per Cubic Foot |
|---|---|---|---|---|---|---|
| Grams Per Cubic Centimeter | 1 | $10^{-3}$ | $6.102 \cdot 10^{-2}$ | 1.730 | 2.768·10 | $1.602 \cdot 10^{-2}$ |
| Kilograms Per Cubic Meter | $10^{3}$ | 1 | 6.102·10 | $1.730 \cdot 10^{3}$ | $2.768 \cdot 10^{4}$ | 1.602·10 |
| Grams Per Cubic Inch | 1.639·10 | $1.639 \cdot 10^{-2}$ | 1 | 2.835·10 | $4.536 \cdot 10^{2}$ | $2.625 \cdot 10^{-1}$ |
| Ounces Per Cubic Inch | $5.780 \cdot 10^{-1}$ | $5.780 \cdot 10^{-4}$ | $3.527 \cdot 10^{-2}$ | 1 | 1.600·10 | $9.259 \cdot 10^{-3}$ |
| Pounds Per Cubic Inch | $3.613 \cdot 10^{-2}$ | $3.613 \cdot 10^{-5}$ | $2.205 \cdot 10^{-3}$ | $6.250 \cdot 10^{-2}$ | 1 | $5.787 \cdot 10^{-4}$ |
| Pounds Per Cubic Foot | 6.243·10 | $6.243 \cdot 10^{-2}$ | 3.810 | $1.080 \cdot 10^{2}$ | $1.728 \cdot 10^{3}$ | 1 |

## COMPLIANCE

| Multiply Number of → BY ↘ To Obtain ↓ | Centimeters Per Dyne | Meton (Meters Per Newton) | Inches Per Ounce |
|---|---|---|---|
| Centimeter Per Dyne | 1 | $10^{-3}$ | $9.136 \times 10^{-5}$ |
| Meton (Meters Per Newton) | $10^{3}$ | 1 | $9.136 \times 10^{-2}$ |
| Inches Per Ounce | $1.095 \times 10^{4}$ | $1.095 \times 10$ | 1 |

## LINEAR MECHANICAL IMPEDANCE

| Multiply Number of → BY ↘ To Obtain ↓ | Dynes Per Centimeter Per Second | Newtons Per Meter Per Second | Ounces Per Inch Per Second |
|---|---|---|---|
| Dynes Per Centimeter Per Second | 1 | $10^{3}$ | $1.095 \times 10^{4}$ |
| Newtons Per Meter Per Second | $10^{-3}$ | 1 | $1.095 \times 10$ |
| Ounces Per Inch Per Second | $9.136 \times 10^{-5}$ | $9.136 \times 10^{-2}$ | 1 |

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